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THESIS

**CREATING SPECIAL OPERATIONS FORCES'
ORGANIC SMALL UNMANNED AIRCRAFT SYSTEM
OF THE FUTURE**

by

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March 2022

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**CREATING SPECIAL OPERATIONS FORCES'
ORGANIC SMALL UNMANNED AIRCRAFT SYSTEM OF THE FUTURE**

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Submitted in partial fulfillment of the
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ABSTRACT

Emerging observations of the Ukrainian conflict reinforce standing assumptions that the future's multidomain operational environment in which U.S. special operations forces (SOF) will deploy will be characterized by rapid, continuous advancements in intelligence, surveillance, and reconnaissance (ISR) technologies. The Department of Defense's inability to develop and field innovative weapons and technical systems at the rate of its peer and near-peer competitors invites great risks to both its military members and its national security. One critical deficiency that U.S. SOF must address immediately is its use of artificial intelligence and machine learning in a small unmanned aircraft system (sUAS). We can no longer assume that we will achieve the air superiority or air parity that have enabled the persistent presence of theater-level assets to support military elements in contested and denied areas. This thesis focuses on enhancing U.S. SOF force protection and situational awareness by combining a cutting-edge sUAS with object recognition software to create an organic ISR capability. Following several field experiments in partnership with private industries to test and refine object recognition software when combined with a sUAS, our results strongly suggest that integrating object recognition capabilities into a SOF element's organic sUAS can achieve the performance parameters necessary to fill the current gap in U.S. SOF force protection and ISR requirements.

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LIST OF ACRONYMS AND ABBREVIATIONS

AI	artificial intelligence
AO	area of operations
ATAK	android tactical assault kit
AV	AeroVironment
DARPA	Defense Advanced Research Projects Agency
DIU	Defense Innovation Unit
DL	deep learning
DOD	Department of Defense
FP	force protection
IP	intellectual property
IPB	intelligence preparation of the battlespace
ISR	intelligence, surveillance, reconnaissance
KLE	key leader engagement
MDO	multi-domain operations
ML	machine learning
PF	partner force
SA	situational awareness
SATLAS	semi-autonomous threat learning alert system
SFOD-A	special forces operational detachment-alpha
SOF	special operations forces
SPOTR	surveillance, persistent observation and targeting recognition
SUAS	small unmanned aircraft system
UAV	unmanned aerial vehicle

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I. INTRODUCTION

In recent decades, U.S. defense strategy has increasingly refocused from its reliance on large concentrations of conventional forces in linear battle spaces to smaller, more surgical and decentralized actions by stand-off weapons and special operations forces (SOF). With these new strategies, U.S. administrations have intensified their reliance on SOF to rapidly achieve asymmetric solutions with minimal logistical requirements or visibility. SOF's ability to use a small tactical footprint to create strategic effects consistently legitimizes them as a choice tool for politically, diplomatically, or militarily sensitive tasks. However, as our national defense strategy evolves toward Chinese and Russian peer adversaries who are currently sprinting to develop and deploy AI-enabled technology that will change the character of war, U.S. forces can no longer be expected to operate with aerial superiority and reliable unrestricted surveillance and communication, yielding the freedom of maneuver and unchallenged supply chains that have enabled us to dominate operating environments with very few casualties.¹

This new focus on defeating or overcoming Chinese- and Russian-led forces' anti-access and area denial systems is the main driving factor behind recent doctrinal changes which acknowledge the complexity of the multi-domain operations (MDO) environment in which the Department of Defense (DOD) will be employed.² Rapid advances in both friendly and adversarial technology, along with questions regarding the ethics and morality surrounding the use of that technology to fight and win wars have further complicated modern warfare.³ While the DOD is attempting to keep pace in this quickly transforming operating environment, the focus of its major policy driven guidance has been on doctrine, training, and intelligence preparation of the battlespace (IPB). For example, the doctrinal

¹ Joseph R. Biden, Jr., *Interim National Security Strategic Guidance* (Washington, DC: Executive Office of the President Washington, DC, 2021), 8, <https://apps.dtic.mil/sti/citations/AD1124337>; Department of Defense, *National Defense Strategy*, 2018, 3, <https://www.defense.gov/Explore/Spotlight/National-Defense-Strategy/>.

² Department of the Army, *U.S. Army in Multi-Domain Operations 2028*, TRADOC Pamphlet 525-3-1 (Fort Eustis, VA: United States Army Training and Doctrine Command, 2018), vii, <https://www.hsdl.org/?abstract&did=820569>.

³ Biden, *Interim National Security Strategic Guidance*, 14.

publication, *The U.S. Army in Multi-Domain Operations 2028*, although it has multiple applicable tenets to the coming changes in warfare, is a classic example of this practice. MDO 2028 fully describes the problem the U.S. will face in future warfare by providing thorough examples of what types of forces the U.S. will need, where they need to be, and what they need to do to be successful. However, it says very little about the types of equipment that will be needed to succeed in this new and incredibly complex operating environment.⁴

Consequently, U.S. SOF, regardless of their tactical and technical proficiency, are losing their comparative advantage against peer and near-peer adversaries as well as the non-state actors who are more adept at adopting the products of technological proliferation and globalization.⁵ Unless we act now to reverse this trend, SOCOM will continue to incur unacceptable risk to its service members in missions similar to the tragic ambush in Niger in 2017.⁶ It is essential and time sensitive that SOCOM enhance SOF team intelligence, surveillance, reconnaissance (ISR) and force protection (FP) capabilities through the provision of modernized tools such as an organic small unmanned aircraft system (sUAS) to enable ground elements to operate independently. Without the timely replacement of legacy systems with augmentations such as organic ISR platforms capable of countering technologically sophisticated adversaries, the future of DOD-enabled national security will be comprised of distant memories of its military advantage, dilapidated cohesion with partners and allies, severely reduced access to international markets, and an irreparable loss of U.S. global influence and prestige.⁷

A. BACKGROUND

The semi-autonomous threat alert system (SATLAS) project is an ongoing effort by students at the Naval Postgraduate School (NPS) to apply the template of leveraging the

⁴ Department of the Army, *U.S. Army in Multi-Domain Operations 2028*, vi–xii.

⁵ Department of Defense, *National Defense Strategy*, 1.

⁶ Alice Friend, “DOD’s Report on the Investigation into the 2017 Ambush in Niger,” Center for Strategic & International Studies, last modified May 15, 2018, <https://www.csis.org/analysis/dods-report-investigation-2017-ambush-niger>.

⁷ Department of Defense, *National Defense Strategy*, 1.

expertise of private sector companies to enhance SOF capabilities, as demonstrated by SOFWERX, DIU, and other similar DOD organizations. The goal of SATLAS is to integrate object recognition software with autonomous operations in a sUAS to significantly increase the situational awareness (SA) and survivability of SOF elements.

The project began under Midgett et. al. in 2019 as they explored the feasibility of the concept using quantitative analysis techniques.⁸ Midgett et. al. studied previous tests conducted by DARPA, which revealed that object detection software could be incorporated into a sUAS that was actively supporting a small unit, significantly increasing its SA, survivability, and decision-making.⁹ They then compared current commercial off the shelf options against existing DOD sUAS capabilities and software. Following that analysis, the team identified four essential capabilities that an organic SOF sUAS should possess: 1) a man-packable platform capable of being integrated with relevant selected software, 2) AI-enabled object recognition or detection software with on-the-edge processing capability, 3) the capacity to operate autonomously, and 4) a common ground control user interface. Understanding their complexity, the team identified these four key pillars as individual research lines of effort.

Following Midgett et. al., Clark continued the project to address the pillar two line of effort, object detection, by partnering with the private sector company Progeny (later AeroVironment) to guide their development of the object detection software to meet the SATLAS team's required performance parameters.¹⁰ Through simulations, Clark piloted the object detection software development to the point where it could identify multiple human and vehicle objects at limited distances in open terrain. A small Nibbler drone served as a surrogate prototype sUAS platform to test the software, with the intent to

⁸ Army Futures Command, *Army Futures Command Concept for Special Operations 2028*, AFC Pamphlet 71-20-4 (Fort Eustis, VA, 2020), 19–26, https://www.army.mil/article/242180/army_futures_command_concept_for_special_operations_2028.

⁹ Defense Advanced Research Projects Agency, “With Squad X, Dismounted Units Partner with AI to Dominate Battlespace,” Defense Advanced Research Projects Agency, last modified July 12, 2019, <https://www.darpa.mil/news-events/2019-07-12>.

¹⁰ William Clark, “Object Recognition in Support of SOF Operations” (master’s thesis, Naval Postgraduate School, Monterey, CA 93943-5000, Naval Postgraduate School, 2021), 23–57, <http://hdl.handle.net/10945/67685>.

eventually transfer the functionality to either an Altavian M440 or Skydio X2D, both of which possess the increased processing power and camera resolution that are key to object detection. Additionally, the M440 and X2D are listed on the Blue sUAS list, confirming their platforms' abilities to accommodate the other three pillars of the SATLAS project.

B. RESEARCH OBJECTIVE

The objective of this research is to guide the refinement and integration of the object detection software to achieve specified performance parameters across varying terrain. To that end, the four major lines of effort are: 1) guiding the developers, 2) selecting software and hardware for the project, 3) refining the performance parameters as needed, and 4) experimenting and conducting simulations with candidate platforms for further work with pillars three and four.

To achieve the objective, I conducted successive iterations of field testing to evaluate the object detection software on various platforms to determine the ways in which the software needs to be refined to successfully augment a SOF team.

The primary research questions are:

1. Can the object detection software be integrated with a sUAS in a way that supports a SOF team's tactics, techniques, and procedures?
2. Can the object detection software and the sUAS be developed to meet the standing performance parameters required to provide SOF ISR and FP?
 - i) What are the technical capabilities and limitations of the object detection software regarding the required performance?
 - ii) How might other sUAS factors need to be modified to enhance the object detection software/sUAS system's ability to support a SOF team?

C. SCOPE AND LIMITATIONS

We advanced prior research on pillar two, guiding the enhancement and integration of object detection software into a sUAS. Pillar one, selecting a sUAS platform, is

addressed only in so far as it impacts or may be impacted by pillar two. Pillar three is marginally explored, and pillar four is not examined in this thesis. Field experimentation and in-person coordination were hampered by travel restrictions from COVID-19. Issues of proprietary restrictions and the possibility of intellectual property (IP) impairment delayed research progress and created technical challenges that forced a fundamental change in the approach to software integration. Limited funding and the condensed timeline have also limited the robustness of experimentation. All field experiments have been restricted to environments within a day's drive of the Naval Postgraduate School campus.

D. ORGANIZATION OF THESIS

Chapter II begins with a vignette to orient the reader, followed by discussions on technology, the future operating environment for SOCOM, the state of objection recognition technology, and prior work by SATLAS and Blue sUAS programs. Chapter III details the methods, observations, and results of the experiments conducted in this stage of the project. Chapter IV provides the analysis of the results along with an estimate on the software/sUAS system's tactical utility, and Chapter V summarizes the findings and proposes recommendations for follow-on work and research.

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II. CONCEPTUAL AND PRACTICAL FRAMEWORK

The content of this chapter is presented in four sections. The first section is a tactical vignette depicting a realistic scenario from the global war on terror during which a sUAS platform would have been an invaluable asset for a special forces operational detachment–alpha (SFOD-A). The second section presents a brief overview of the technological revolution and how it has enabled peer and near-peer competitor pursuits and ambitions. The third section reviews current U.S. defense policy and doctrinal approaches to future military operations from the strategic to the tactical level in the context of emerging technological threats. The final section discusses prior work on SATLAS and similar programs to advance SOCOM’s capabilities to equip SOF teams to succeed in the MDO.

A. TACTICAL VIGNETTE

During the early morning hours of one of the last winters of the twenty-year war on terror, a SFOD-A prepared to depart their forward operating base to conduct a key leader engagement (KLE) with a friendly local partner force (PF). The PF base was situated deep in one of the more mountainous regions of SOCOM’s Area of Operations (AO). Because of its remote location and consequential risk of harboring a heavy presence of enemy combatants, the SFOD-A elected to utilize helicopters to expeditiously travel to and from the KLE. Although several KLEs had been conducted between the PF and SFOD-As in this region without incident in the past, this engagement was the first between the PF and this SFOD-A due to the team’s recent assumption of responsibility for the AO. It was not uncommon for enemy combatants to be throughout the region. This transition was no exception.

Once the SFOD-A had gathered the weapons, ammo, and communication equipment needed for the engagement, they confirmed with their battalion leadership that the mandatory armed theater level unmanned aerial vehicle (UAV) was available and on standby. Shortly after noon, following the battalion’s reconfirmation that the theater asset was in position, the SFOD-A’s helicopters flew to the site of the KLE.

The helicopter infiltration and the KLE were conducted as rehearsed and without incident. Approximately two hours prior to dusk, the SFOD-A went through the final formalities that typically accompany the end of a successful meeting and prepared to exit the two-story compound in which the KLE had been conducted. In accordance with the SFOD-A's standard operating procedures, the team's security element was the first to exit the compound into the adjacent courtyard to monitor all major entry and exit points from the partially urban and rural areas surrounding the compound. Although the SFOD-A security element covered the entry and exit points of the compound with their light and heavy machine guns, they understandably gave little attention to the compound in which they had spent the last several hours. Shortly after security was set, the SFOD-A's team leader exited the compound, still amicably conversing with the PF leaders. They believed they were nearing the completion of another successful mission, but their night was far from over.

Within moments of the SFOD-A leaders exiting the front doors of the compound, a machine gunner from the second floor of the compound began spraying both the SFOD-A and nearby PF members in the courtyard with bullets. Within the first few seconds of the ambush by what appeared to be a member of the friendly PF element, several members of the SFOD-A and PF had been killed or wounded. Less than a minute into ambush, the machine gunner who had initiated the ambush was killed as well, thanks to the quick reactions of members of the SFOD-A near the entrance of the compound.

The next few hours were heart-wrenching, confusing, and terrifying for the surviving members of the SFOD-A on the ground. As nightfall approached, the majority of the SFOD-A continued to fight despite several bullet wounds and increasing levels of blood loss. The team leadership methodically attempted to consolidate what was left of the team while keeping headquarters informed on the worsening situation. With wounded key leaders and radio equipment that was riddled with bullet holes, this task proved extremely difficult. Amid the confusion, some of the team continued sporadic firefights with individuals whom they could not effectively discern as friend or foe, while others continued to assess and treat the wounds of the injured team and PF members. The "fog of war" was real for the team. Their confusion and reduced SA severely limited the usefulness of the

theater level UAVs that had decimated so many enemy combatants, vehicles, and compounds in the past.

The battalion headquarters monitored the events as they unfolded via satellite communication and theater level UAV feeds while a quick reaction force boarded another set of helicopters to relieve the SFOD-A in contact. Although the theater UAV was armed with enough firepower to destroy all the enemy combatants, the uncertainty of the situation prevented the UAV operators from engaging any of them.

What the SFOD-A on the ground critically needed was a small, organic ISR asset that could rapidly detect friendly and enemy elements when their own mobility and communications equipment were severely limited. A man-packable sUAS capable of accurately identifying entities, would have greatly enhanced the team's SA and survivability.

There were several chronological points in this vignette during which a sUAS could have enhanced the team's SA and FP, conceivably enabling them to prevent or significantly mitigate the effects of the ambush.

- During the infiltration, as the team approached the village where the KLE was to be conducted, an organic sUAS might have identified the positions of all entities armed with machine guns in and around the compound. This would have provided the team with quick, high interest points of reference prior to entering and exiting the compound several hours later.
- During the KLE, an organic sUAS could have continued to surveil the compound and the surrounding area for suspicious activity. A sUAS would provide the SFOD-A with increased SA on preferred routes toward the exfiltration site, as well as the location of machine gunners around the compound.
- At the conclusion of the KLE, an organic sUAS could have augmented the security element, identifying the machine gunner as a possible threat prior

to the team leader exiting the compound, providing the team with an opportunity to diffuse the situation before it began.

- During the ambush, an organic sUAS might have aided SFOD-A leadership by identifying the locations of all friendly elements, drastically expediting the consolidation of men, weapons, and equipment prior to the team's exfiltration.
- During the exfiltration, an organic sUAS might have assisted the team in positively identifying enemy combatants as the team moved toward the exfiltration site. This intelligence might have enabled the theater level UAV operator to engage and destroy the threats in the area.

This scenario is based upon real events that occurred in the global war on terror. As SOF face more complex MDO environments in peer and near peer conflicts, their access to communication and theater level assets will be reduced and the risk to troops will greatly increase. We cannot afford to ignore the ISR and FP implications that the emerging MDO context anticipates. For SOCOM small SOF elements, an organic ISR and FP platform should now be considered an indispensable asset.

B. TECHNOLOGICAL TRENDS DRIVING SOF AUGMENTATION

The discussion now shifts to technology and the confusion and controversy surrounding artificial intelligence (AI) and machine learning (ML). The developing situations with China and Russia and their ambitious technological goals and objectives that make the sUAS platform so critical will also be reviewed.

1. The Technological Revolution

In the last several decades, what many describe as the third revolution of warfare or the fourth industrial revolution, has driven technology to evolve from a detachable piece of machinery used to accomplish simple tasks, to an inseparable necessity that is

interwoven throughout human experiences and interactions twenty-four hours a day.¹¹ Along with the enormity of benefits that the technological revolution has yielded for international societies, comes an uncharted, intricate security environment that is also defined by rapid change.¹² Exploitable advancements in visual perception, speech and facial recognition, advanced computing, robotics, AI, ML, computer vision, data analytics, hypersonics, directed energy, and biotechnology are just a few of the products of technology that have changed the way state and non-state actors survive, thrive, and during conflicts, how they fight.¹³

Given its continuous rapid development, there are very few standing rules or policies by which any state can effectively govern the military's use of technology.¹⁴ The vehicles, drones, weapons, etc., in which the world has incorporated AI and ML introduce risks ranging from fallibility, unpredictability, and vulnerability to subversion and data poisoning, creating ongoing issues that leading innovators in the U.S. are constantly attempting to resolve.¹⁵ The DOD has therefore made it a point to maintain a human within the decision-making loop for accountability and complex critical thinking purposes, to minimize the unintended effects of AI-augmented weapon systems, despite knowledge that some of its adversaries are unwilling to do the same.¹⁶ In the same way, sharing data and information in pursuit of AI and ML innovation also has ethical and legal ramifications that the U.S.' competitors do not necessarily share due to their societies of secrecy and minimal trust.¹⁷

¹¹ James Johnson, "Artificial Intelligence & Future Warfare: Implications for International Security," *Defense & Security Analysis*, Artificial intelligence and future warfare, 35, no. 2 (April 3, 2019): 147–169, <https://doi.org/10.1080/14751798.2019.1600800>.

¹² Department of Defense, *National Defense Strategy*, 1.

¹³ Department of Defense, 3; James Johnson, "Artificial Intelligence, Drone Swarming and Escalation Risks in Future Warfare," *The RUSI Journal* 165, no. 2 (February 23, 2020): 26–36, <https://doi.org/10.1080/03071847.2020.1752026>.

¹⁴ Biden, *Interim National Security Strategic Guidance*, 8–9.

¹⁵ Johnson, "Artificial Intelligence, Drone Swarming and Escalation Risks in Future Warfare," 27.

¹⁶ Johnson, 29–30.

¹⁷ Rand Waltzman et al., *Maintaining the Competitive Advantage in Artificial Intelligence and Machine Learning* (RAND Corporation, 2020), 9–17, <https://doi.org/10.7249/RRA200-1>.

Therefore, with a current lack of regulations, amid the seemingly limitless possibilities in this new technological world, those with power along with those seeking power have incessantly pursued initiatives to develop and deploy technology that will provide an advantage over their competitors or adversaries before these advancements are deemed globally intolerable.¹⁸ U.S. competitors specifically, after searching for vulnerabilities within America's power structure, have discovered weaknesses in asymmetric techniques and hybrid warfare.¹⁹

It is this conundrum that has caused much of the debate between U.S. political officials and leading military strategists. The U.S., its major allies, and their adversaries have all recognized the revolutionary potential of AI and ML in regard to national security, making the question of what to do about it no longer avoidable.²⁰ How can the U.S. shape the ethical and normative frameworks for technology products similar to AI, as it did with the atomic bomb, when it is not the global leader in AI development?²¹ How can the U.S. confidently argue that DOD should limit the use of algorithms in independent decision-making and structuring, when it is fully aware that its adversaries currently do not, and will not include similar limitations now or in the near future?²² I propose that an organic sUAS for U.S. SOF elements, that maintains a human within the decision making loop, is a logical approach to address this critical warfighter gap.

2. Technology in Great Power Competition

Following the unremarkable end to the global war on terror, the U.S. has shifted its attention to potential inter-state large scale confrontation with its strategic competitors,

¹⁸ Biden, *Interim National Security Strategic Guidance*; Department of Defense, *National Defense Strategy*, 8, 14.

¹⁹ John Taft, Liz Gormisky, and Joe Mariani, "Special Operations Forces and Great Power Competition: Talent, Technology, and Organizational Change in the New Threat Environment," Deloitte Insights, last modified June 17, 2019, <https://www2.deloitte.com/us/en/insights/industry/public-sector/future-of-special-operations-forces-great-power-competition.html>.

²⁰ Johnson, "Artificial Intelligence & Future Warfare," 149.

²¹ Biden, *Interim National Security Strategic Guidance*, 14.

²² Joint Special Operations University, *Special Operations Research Topics 2022* (MacDill AFB, FL: Joint Special Operations University Press, 2021), 2, <https://jsou.libguides.com/jsoupublications/researchtopics>.

China and Russia.²³ Coinciding seemingly directly with technological growth, China's assertiveness and Russia's destabilizing tendencies have aggressively grown within recent decades as both ardently pursue advancements that accurately target and counter U.S. strengths.²⁴ In many professional opinions, including that of retired Lieutenant General Ken Tovo, our adversaries have been making advancements in these technological areas in a much more efficient manner than America has managed to recently, ultimately exposing U.S. citizens to tech-centric digital, physical, and political threats.²⁵ Russia's engagement in sophisticated cyber-attacks on U.S. elections and Ukrainian infrastructure, and China's rapid advancements in hypersonic weapons, spurred by a heavily funded research and development infrastructure that has enabled China to conduct twenty times more hypersonic tests than the United States, are two examples of these threats.²⁶

China's military modernization, coercive economics, and influential information operations have begun what may be an irreversible reordering and restructuring in the Indo-Pacific.²⁷ China has created an AI-innovation agenda at the national level with the goal of expediting "civil-military fusion" to adapt to the global security transformation that is currently taking place.²⁸ Organizations such as the RAND corporation assess that China's authoritarian practices and their consequential ability to generate a "whole-of-regime" approach have enabled China to concentrate resources and focus in pursuit of AI and ML advances in a way that most democracies could not.²⁹ China's achievements in drone swarm sophistication exceed similar efforts by the U.S. and its allies in many ways, clearly

²³ Joint Special Operations University, 4.

²⁴ Biden, *Interim National Security Strategic Guidance*, 8, 14.

²⁵ Taft, Gormisky, and Mariani, "Special Operations Forces and Great Power Competition."

²⁶ Helley M. Saylor, "Hypersonic Weapons: Background and Issues for Congress" (Washington, DC: Congressional Research Service, July 11, 2019), 13.

²⁷ Department of Defense, *National Defense Strategy*, 2.

²⁸ Johnson, "Artificial Intelligence & Future Warfare," 157.

²⁹ Waltzman et al., *Maintaining the Competitive Advantage in Artificial Intelligence and Machine Learning*, 14.

demonstrating how their whole-of-nation approach can rapidly advance progress with sUAS platforms.³⁰

Similarly, Russia has begun the process of refocusing its military structure with the goal of having 30% of its military capabilities robotic by the end of 2025.³¹ Russia has used emerging technologies to counter, subvert, and discredit the governments of Georgia, Crimea, and most recently Ukraine.³² A renewed focus on light unmanned reconnaissance platforms, following the conflict with Georgia have resulted in the creation and fielding of thousands of drones into Russian ground force formations within the last decade.³³ Russia has also focused heavily on modernizing their own nuclear arsenal, creating a level of tension in Eastern Europe that the world has not felt since the end of the Cold War.³⁴ With Russia's active nuclear proliferation and modernization, discussions concerning using AI and ML to monitor competitor countries' creation, activation, and test launches of nuclear weapons have also been ongoing.³⁵ Tasks such as passive monitoring of these nuclear sites in denied territories where theater level UAVs and reconnaissance planes are incapable of flying, could be accomplished by small organic sUAS platforms.

As U.S. competitors' ambitions and capabilities continue to rapidly increase, U.S. reliance on AI to create ISR, analytical, and kinetic solutions to counter adversarial development becomes progressively undeniable.³⁶ Each year, additional challenges from every domain create a more deadly and disruptive battlefield with the potential to devastate the U.S. and its allies at the tactical level as well as within their respective homelands.³⁷

³⁰ Scott N. Romaniuk and Tobias Burgers, "China's Swarms of Smart Drones Have Enormous Military Potential," *The Diplomat* 3, no. 02 (2018).

³¹ Johnson, "Artificial Intelligence & Future Warfare," 148.

³² Department of Defense, *National Defense Strategy*, 2.

³³ Anton Lavrov, *Russian Military Reforms from Georgia to Syria* (Washington, DC: Center for Strategic and International Studies (CSIS), 2018), 8–10.

³⁴ Department of Defense, *National Defense Strategy*, 2.

³⁵ Johnson, "Artificial Intelligence & Future Warfare," 152–153, 158.

³⁶ Department of Defense, *National Defense Strategy*, 6; Joint Special Operations University, *USSOCOM Library*, 14.

³⁷ Department of Defense, *National Defense Strategy*, 1.

For these reasons, the U.S. has begun to more adamantly explore high tech drones and their ability to provide U.S. forces and their allies advantages similar to China’s drone swarms and Russia’s light reconnaissance drones.³⁸ The DOD’s current goal is to be able to effectively deploy and employ forces through several layers of time, space, and function, providing the level of standoff necessary to defeat Russia and China in a MDO environment.³⁹ This new MDO environment, along with how an organic sUAS platforms will enhance SOF elements operating in these areas, will be discussed in the following sections.

C. GUIDANCE ON SOF IMPROVEMENT

This section reviews strategic, operational, and tactical guidance from the most recently published *Interim National Security Strategy*, *National Defense Strategy*, *National Military Strategy*, *Special Operations Research Topics 2022*, and *The U.S. Army in Multi-Domain Operations 2028*. Additionally, data surrounding the weapons systems used to determine the appropriate parameters for an organic sUAS will be addressed. Altogether, this will set the groundwork upon which the goals of SATLAS and similar sUAS programs in the following section are based.

1. The Challenges of MDO

The primary focus of sUAS platforms and similar technological advancements in the arsenal of the U.S. and its allies, will be to defeat the two structures that have made China and Russia so successful in their recent exploits: anti-access and area denial systems.⁴⁰ The anti-access and area denial schemes are systematic approaches to prevent the U.S. and its allies from gaining access to the areas necessary to achieve dominance through the air, land, and maritime battle techniques that have brought significant levels of success during past conflicts.⁴¹ MDO anticipates that SOF elements operating deep within

³⁸ Joint Special Operations University, *USSOCOM Library*, 34.

³⁹ Department of the Army, *U.S. Army in Multi-Domain Operations 2028*, iii.

⁴⁰ Department of the Army, vii.

⁴¹ Department of the Army, vii.

these environments will have to rely on platforms such as organic a sUAS for ISR and FP, due to the contested airspace preventing the presence of theater level UAVs and other support aircraft. In other words, if our adversaries are successful, the strategic and operational stand-off resulting from their anti-access and area denial systems would virtually cripple joint forces' ability to engage and defeat Russia and China using doctrine and legacy systems from the past few decades.⁴² The U.S. cannot expect success in future conflicts while using outdated equipment.⁴³ Although military advancements in AI and ML have been slow and methodical due to the distractions of the global war on terror and other political ambitions, recent changes in training doctrine and operating concepts are rapidly integrating advanced technologies as force multipliers, consequently steering federal goals back towards the right direction.⁴⁴

According to MDO 2028, the emerging strategic environment of competition between the U.S. and peer and near-peer adversaries is defined by four trends: 1) adversaries contesting throughout all domains; 2) an expanded battlefield that is navigated by smaller, more lethal armies; 3) state actors struggling to impose their will; and 4) lesser states more effectively resisting deterrence and competing below the level of armed conflict.⁴⁵ Due to the complexity of this atmosphere, it is only through burden sharing, while focusing on building its own, partner, and allied capacities, that the U.S. can realistically hope to remain a preeminent global military force capable of defeating a sophisticated Chinese or Russian information operations and unconventional warfare campaign.⁴⁶ The best way to accomplish this goal, short of armed conflict, is through

⁴² Department of the Army, vii.

⁴³ Department of Defense, *National Defense Strategy*, 6.

⁴⁴ M L Cummings, *Artificial Intelligence and the Future of Warfare*, International Security Department and U.S. and the Americas Programme (London, England: Chatham House, the Royal Institute of International Affairs, 2017), 1; John M. Fossaceca and Stuart H. Young, "Artificial Intelligence and Machine Learning for Future Army Applications," in *Ground/Air Multisensor Interoperability, Integration, and Networking for Persistent ISR IX*, vol. 10635 (Ground/Air Multisensor Interoperability, Integration, and Networking for Persistent ISR IX, International Society for Optics and Photonics, 2018), 1063507, <https://doi.org/10.1117/12.2307753>.

⁴⁵ Department of the Army, *U.S. Army in Multi-Domain Operations 2028*, iv.

⁴⁶ Biden, *Interim National Security Strategic Guidance*, 14, 19; Department of Defense, *National Defense Strategy*, 4; Department of the Army, *U.S. Army in Multi-Domain Operations 2028*, xi.

prioritizing the U.S.’ preparedness for war in the high tension areas of the Indo-Pacific, Middle East, and Europe.⁴⁷

By enhancing a SOF element with an organic sUAS, the SOCOM could take large strides toward successfully engaging in combat along the lines of the four aforementioned trends of MDO 2028. A SOF unit, or a smaller more lethal element capable of operating in an expanded battlefield, could in effect impose a state actor’s will against lesser states below the level of armed conflict across multiple domains by simply executing its twelve special warfare and surgical strike core activities. From delivering military information support operational messages in remote denied territory, to reconnoitering nuclear arsenals or long-range artillery assets, a SOF element augmented by an organic sUAS could be the ideal asset in a future MDO environment. The following section will elaborate on these capabilities in more detail.

2. Operational and Tactical Challenges

In a future multidomain operating environment that calls for a small, lethal, resilient, versatile team is needed for success, the obvious solution is SOF.⁴⁸ When considering the applicability of technology to modern warfare, leading authorities such as Lt Gen(R) Tovo and Dr. Michael Vickers, former Undersecretary of Defense for Intelligence, agree that SOF is the appropriate spearhead for AI and ML augmented weapons and machinery.⁴⁹ The US’s historical risk-averse overemphasis on exceptional performance over timely implementation and modular upgrades has led to the current status of ill-equipped U.S. SOF elements.⁵⁰ To recover from this predicament, the U.S. needs a more powerful, modernized SOF unit that is properly equipped and capable of competing in the grey zone, which is the area between what is characteristically identified as the zones of war and peace.⁵¹

⁴⁷ Department of Defense, *National Defense Strategy*, 6.

⁴⁸ Department of Defense, 6.

⁴⁹ Taft, Gormisky, and Mariani, “Special Operations Forces and Great Power Competition.”

⁵⁰ Department of Defense, *National Defense Strategy*, 10.

⁵¹ Biden, *Interim National Security Strategic Guidance*, 14.

To successfully compete in the grey zone, it has been argued that SOCOM investments need to focus on tools, such as the sUAS, that enhance a SOF element's ability to deploy, operate, maneuver, survive, and regenerate while in denied environments. AI, ML, big data, and the rapid application of their decision assistance capabilities are what SOF need to become more attuned, knowledgeable, and effective in a MDO environment.⁵² Specifically, sUAS that enhance visualization and interface techniques, facilitate timely decisions and analysis, reduce cognitive workload, and improve the observe, orient, decide, act (OODA) decision making loop could enable SOF to compete and counter similar adversary capabilities.⁵³ Experimenting with sUAS that support these tasks and functions during joint exercises could help to enable the rapid incorporation of innovative ideas between the U.S. and its allies to create a much needed competitive advantage.⁵⁴

If SOF elements are equipped with an organic sUAS, they can begin plan, train, and prepare to counter competitor's anti-access and area-denial systems through a variety of actions as highlighted in Figure 1. Concerning the tenets of MDO, whether a SOF element is serving as a forward presence or expeditionary force, conducting independent maneuver or creating cross-domain synergy through the coordination of cross-domain fires, their potential to accomplish these missions could be amplified with an organic sUAS.

⁵² Joint Special Operations University, *USSOCOM Library*, ix.

⁵³ Joint Special Operations University, 16–17.

⁵⁴ The Joint Staff, *National Military Strategy*, 2018, 4, <https://history.defense.gov/Historical-Sources/National-Military-Strategy/>.

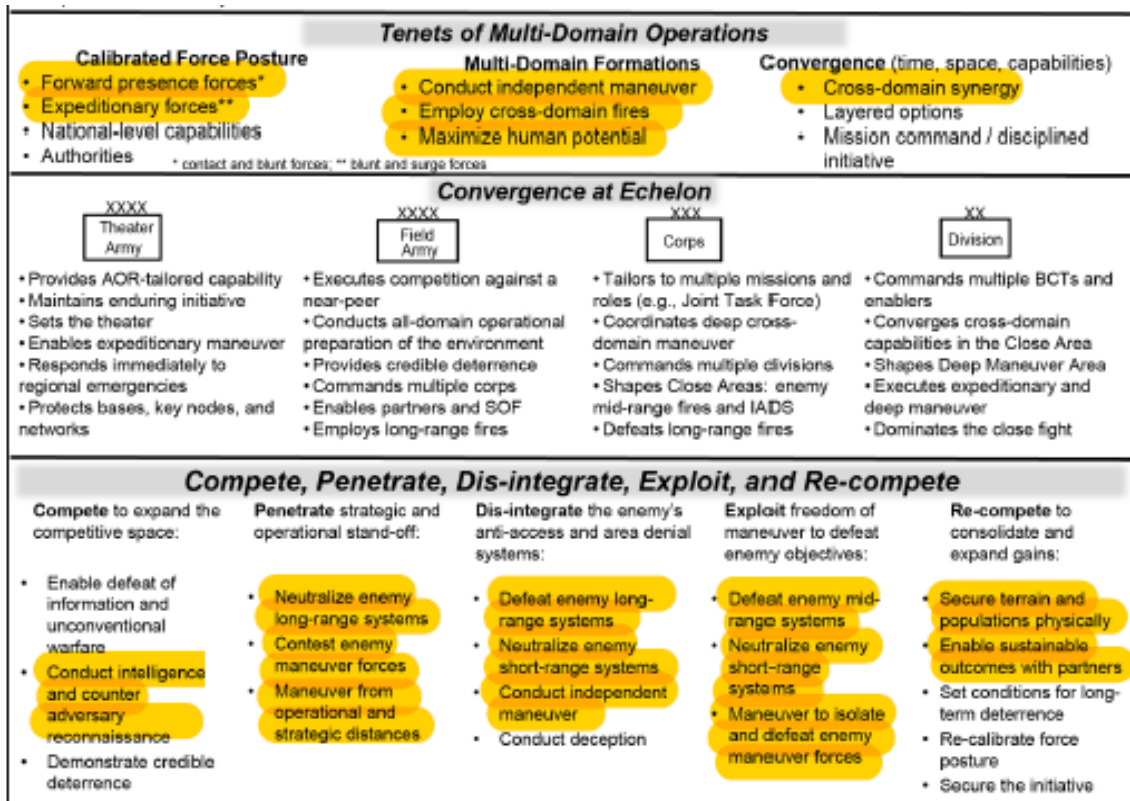


Figure 1. SOF Missions in MDO⁵⁵

Similarly, in the context of the sequential phases envisioned in the MDO, an sUAS with object recognition could support an SFODA when performing numerous functions such as those highlighted at the bottom of Figure 1. **Compete:** An organic sUAS that is equipped with object recognition could greatly enhance a SOF unit's ability to conduct ISR to discover and counter enemy elements in a variety of terrain settings. **Penetrate and Dis-Integrate:** An organic sUAS could enhance a team's force protection in the deep fires area by improving their ability to successfully avoid detection by increasing the level of standoff while identifying artillery assets and observing maneuvering enemy forces for targeting in denied territory. **Exploit:** The ability to isolate, or coordinate with other PF or conventional elements to enable them to isolate and defeat enemy forces is greatly enhanced through organic ISR assistance. **Re-compete:** A SOF element working with a PF element to secure and maintain control of a population in contested territory could be dramatically enhanced

⁵⁵ Adapted from Department of the Army, *U.S. Army in Multi-Domain Operations 2028*, v.

through the capabilities provided through an organic sUAS platform being used to monitor avenues of approach or areas of vulnerability during continuous operations. These tasks, although conducted in the past by SOF elements without an organic sUAS platform, could be conducted more reliably, more effectively, and with less risk by a SOF element augmented by an organic sUAS.

3. SUAS Performance Parameters

In order to minimize the risk posed to a SOF element, an organic sUAS should be able to detect entities while SOF is outside of the maximum effective range of enemy combatant weapon systems. This would provide a team with sufficient lead time to assess and react to potential threats before being decisively engaged. Small arms weapon systems are the arms most likely to be used by a ground force against a small element operating in denied territory. For this reason, the maximum effective range of these systems will be used to determine the minimal acceptable object recognition range of an organic sUAS.

The small arms weapons most commonly assigned to standard ground force elements are machine guns, grenade launchers, and rifles. Machine guns are usually considered the highest casualty producing weapon at short ranges and are therefore a priority for identifying and engaging in combat operations. The ammunition for a machine gun ranges from 5.45 mm to 14.5 mm rounds, with the capacity to effectively engage an enemy at several hundred meters when mounted on a bipod or tripod.⁵⁶ For example, while weapon systems such as the shoulder fired Uzi Pro Israeli 9mm Submachine Gun has a max effective range of approximately 100 meters, weapons such as a general purpose machine gun that fires 7.62mm rounds from a bipod or tripod has a max effective range of 800 meters.⁵⁷

Grenade launchers and rocket propelled grenades are two other examples of heavy casualty producing weapons found in small maneuver elements. Although typically less

⁵⁶ GlobalSecurity.org, “Small Arms and Light Weapons (SA/LW),” GlobalSecurity.org, 2013, <https://www.globalsecurity.org/military/systems/ground/small-arms.htm>.

⁵⁷ GlobalSecurity.org; and British Army, “Small Arms and Support Weapons,” Army Be the Best, accessed March 6, 2022, <https://www.army.mod.uk/equipment/small-arms-and-support-weapons/>.

common than machine guns among western ground forces, these weapon systems would also be critical to identify prior to a SOF element maneuvering within their maximum effective range. Single shot grenade launchers are among the most common grenade launchers used in combat theaters, firing either 30 or 40 mm high explosive grenades to a max effective range of around 350 meters for weapons such as an underslung grenade launcher attached to a British SA80.⁵⁸ Rocket propelled grenades similar to the Russian RPG-7 have a maximum effective range between 330 and 500 meters depending on the model.⁵⁹

Rifles are the most prevalent small arms weapon currently in use today. The ammunition used in a rifle is usually either a 5.56 or 7.62 mm round, fired one shot at a time when accuracy and range are taken into consideration.⁶⁰ Although the rifle is not a heavy casualty producing weapon, it still can cause significant damage to small maneuver element when employed in significant numbers. Some of the best and most popular rifles being used in modern warfare, such as the British SA-80 and the AK-47, have a maximum effective range of approximately 400 meters.⁶¹

With the maximum effective ranges of the most common weapons systems taken into consideration, an organic sUAS platform should be able to detect an entity in open terrain at preferably 900 meters, but no less than 500 meters from a maneuvering SOF element. The complexity of an urban or wooded terrain would greatly reduce the range of sight and alter the line of fire for both friendly and enemy elements, causing an organic sUAS's role to shift to more proactive requirements. In these scenarios, multiple platforms would likely be needed to maximize the situational awareness and force protection of a maneuvering SOF element, preferably identifying threats outside of 100 meters when possible.

⁵⁸ GlobalSecurity.org, "Small Arms and Light Weapons (SA/LW)"; and British Army, "Small Arms and Support Weapons."

⁵⁹ Worldwide Equipment Guide, "ODIN – OE Data Integration Network," ODIN, accessed March 6, 2022, <https://odin.tradoc.army.mil/Search/WEG/small%20arms%20weapons>.

⁶⁰ GlobalSecurity.org, "Small Arms and Light Weapons (SA/LW)."

⁶¹ British Army, "Small Arms and Support Weapons."

D. PRIOR WORK

This section describes the work in SATLAS and similar Blue sUAS programs that informed the writing and experiments described in this thesis. Each of these programs are described in the following segments. The first segment provides a review of key terms to provide further clarification in the specificities of the SATLAS project's overall objective. The second section discusses the benefits of autonomous sUAS platforms and DIU's Blue UAS program. The third segment discusses the Defense Advanced Research Projects Agency's (DARPA) Squad X Experiments, and the last section characterizes object recognition.

1. Key Terms

Mary Louise, or M. L. Cummings, provides a reasonable and admittedly oversimplified definition of AI in her article "Artificial Intelligence and the Future of Warfare" as "the capability of a computer system to perform tasks that normally require human intelligence, such as visual perception, speech recognition, and decision making."⁶² Cummings also distinguishes between automated and autonomous systems, specifying that automated systems use rule-based deterministic algorithms where for each input, the output will always be the same; while autonomous systems make informed assumptions about an optimal course of action based upon varying sensor input.⁶³

According to Fossaceca and Young in "Artificial Intelligence and Machine Learning for Future Army Applications," ML is "improving machine knowledge and performance via interactions with the environment, data, people, etc."⁶⁴ Deep learning (DL) is the ability of a platform to use algorithms to conduct onboard processing of data from a camera or sensor, resulting in immediate reactions or responses to the stimuli being processed.⁶⁵

⁶² Cummings, *Artificial Intelligence and the Future of Warfare*, 2.

⁶³ Cummings, 3–4.

⁶⁴ Fossaceca and Young, "Artificial Intelligence and Machine Learning for Future Army Applications."

⁶⁵ Clark, "Object Recognition in Support of SOF Operations," 15–16.

The sUAS envisioned by SATLAS would be an autonomous drone capable of using AI, ML, and deep learning. With these features, the sUAS platform would enhance a SOF element's situational awareness, survivability, and FP across a range of missions and operations during MDO.

2. The Autonomous sUAS and DIU's Blue UAS Program

A robust body of scholarly and professional literature predict how AI-enabled platforms will play an increasingly important role in future warfare. Experiments such as those conducted at the Maneuver Battle Lab at Fort Benning, GA, help to clarify the tactical value of aerial platforms. By conducting controlled experiments both with and without AI-enabled ground and aerial robots, the experimenters recorded that the aerial platforms accounted for a 92% increase in the operating platoon's combat effectiveness, while the ground robots failed to provide any statistical significance to the platoon's combat effectiveness.⁶⁶ Informed by that research, Midgett et. al decided to pursue AI-enabled aerial platforms to augment SOF elements.

The Blue UAS program was initiated by one of the leading innovation conduits between the commercial and the federal sector, the Defense Innovation Unit (DIU). Blue UAS focuses on rapidly identifying, vetting, prototyping, modifying, and scaling top of the line UAS commercial projects for the DOD's use.⁶⁷ sUAS platforms that are vetted and approved through DIU's process are then afforded the opportunity to bypass the extensive and timely bureaucracy needed to deliver technologically relevant equipment the field. This has significantly reduced the timeline from discovery to fielding in accordance with the National Defense Strategy.

3. DARPA Squad X Experiments

From 2018 to 2019, DARPA conducted its Squad X Experimentation program to discover and build on data demonstrating how AI could augment a warfighting force. The

⁶⁶ Clark, "Object Recognition in Support of SOF Operations," 21.

⁶⁷ Defense Innovation Unit, "UAS Solutions for the U.S. Government.," Defense Innovation Unit, last modified 2021, <https://www.diu.mil/blue-uas>.

experiments began in 2018 with AI-enabled systems created by CACI's BITS and Lockheed Martin, focusing on developing the capability to provide ground units with intelligence that could support their tactical tasks. They furthered their research and development during ongoing training combat scenarios. These experiments were built upon in 2019 when autonomous aerial, cyber, and ground systems were tested by Marine squads at Twentynine Palms. The autonomous systems continuously surveiled the area ahead of and to the flanks and rear of the perimeter of the squad, providing them with real-time updates on a handheld Android Tactical Assault Kit (ATAK). Through constant input from AI-enabled systems, the Marine squads gained enhanced SA, allowing ample time to be proactive to the stimuli in their environment.⁶⁸

The Squad X experiments were some of the first experiments of their kind to demonstrate how AI can assist a small maneuver element in its standard operating tasks without creating a cognitive overload in a human-in-the loop system.⁶⁹ After studying the results of that research, Midgett et. Al and later Clark began collaborating with AeroVironment to create object recognition software to improve upon the progress revealed during the Squad X experiments.

4. Object Recognition

Object recognition software development was the focus of Clark's research in support of pillar two of the SATLAS program. The private sector company responsible for creating and updating the object recognition software is AeroVironment (AV), formally known as Progeny Solutions. AV created the Surveillance, Persistent Observation and Targeting Recognition (SPOTR) suite that was utilized by CACI's BITS and Lockheed Martin's robots during the SQUAD X experiments described in the previous segment. SPOTR was originally developed to integrate into a sUAS, in order to use its algorithms in

⁶⁸ Defense Advanced Research Projects Agency, "With Squad X, Dismounted Units Partner with AI to Dominate Battlespace."

⁶⁹ Clark, "Object Recognition in Support of SOF Operations," 19.

conjunction with the platform's onboard computer vision to detect, identify, categorize and track entities of interest.⁷⁰

Object recognition is a complex process. It requires an enormous amount of time and data to fully develop the algorithms to the point where they can accurately and consistently detect and identify entities of interest. Several quality images from differing angles of one entity of interest are required to allow DL through neural networks to develop the software to identify that same object from different altitudes and angles in real time.⁷¹ Various external and internal influencers, from natural terrain obstructions to the number of pixels present in a particular sUAS platform's camera, impact the effectiveness of the SPOTR software.⁷² For these reasons, companies often spend hundreds of hours working with their object recognition software, confirming or denying successful entity identifications of a certain type in order to train the algorithms to accurately identify those same entities during live exercises in field experiments.

Companies like Anduril have developed similar initiatives with object recognition software in differing forms. Anduril uses a product called Lattice to create an environment through which objects of interest can readily be detected by static and kinetic equipment linked to the Lattice network, vastly increasing the SA of the user in a given area. Lattice's functionality is dependent upon an extremely powerful sensor tower that creates a mesh network through which computer vision, ML, AI, sensor fusion, and edge computing all contribute to detect, identify, classify and track entities of interest within the tower's range in a way similar to AV's SPOTR technology.⁷³

⁷⁰ Clark, 18.

⁷¹ Clark, 18.

⁷² Clark, 76.

⁷³ Anduril Industries, "Anduril — Lattice," Anduril, last modified 2021, <https://www.anduril.com/lattice/>.

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III. METHOD

This chapter explains my approach to achieve the objectives of this phase of the SATLAS project. I tested and evaluated the object detection software and various sUAS platforms in field experiments and simulations to assess its functionality when integrated with an approved Blue sUAS. In addition to these experiments, I provided progressive guidance to the software developers regarding the software’s ability to meet our minimal performance parameters for ISR and FP as described in Chapter II.

The experiments encompass four phases. Figure 2 illustrates how each phase is nested with my defined major lines of effort from Chapter I, while Table 1 details their respective objectives. Each phase is divided into three separate sections: the purpose, action, and the observations sections. The purpose section provides a brief explanation of the tasks and goals of that phase to highlight the parameters and expectations for that phase. The action section provides a detailed breakdown of the experiment set-up, manipulations, and changes where applicable to facilitate any similar experiments in the future. The observations section discusses the data and results of the experiments that are analyzed in more detail in the following chapter, Analysis.

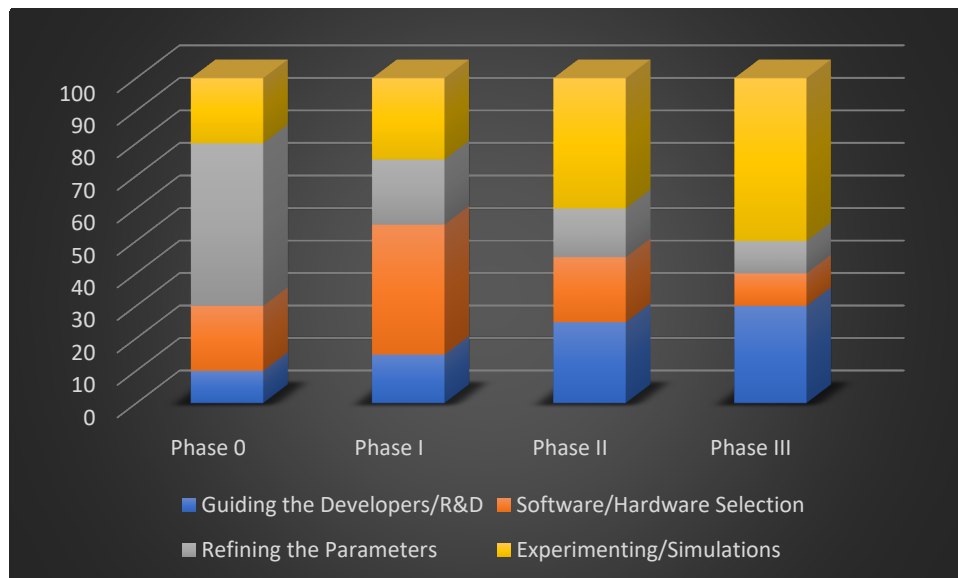


Figure 2. SATLAS Major Lines of Effort

Table 1. Experiment Objectives

Phase 0 – Gain SA and Provide Guidance	Objective 1: Evaluate simulation results and status of capstone objectives
	Objective 2: Familiarize with SPOTR software R&D
	Objective 3: Provide initial guidance to continue further software development
Phase I – Equipment Down Select	Objective 1: Select Blue sUAS for further experimentation
	Objective 2: Explore ways to expedite object detection software development
Phase II – Discovery Experiment	Objective 1: Guide integration of selected Blue sUAS with object detection software
	Objective 2: Conduct simple tests w/ sUAS platforms using Key-Length-Value (KLV) metadata
Phase III – Hypothesis Generating Experiments	Objective 1: Refine required performance parameters of object detection software
	Objective 2: Evaluate object detection software during sUAS autonomous activity

A. PHASE 0: GAIN SA AND PROVIDE GUIDANCE

In Phase 0, I gained an understanding of the current status of the object detection software through meetings and simulations during which AV provided updates on the progress of their research and development (R&D) department. We used this information to refine the parameters and guide AV developers and priorities.

As illustrated in Figure 2, most of this phase consisted of refining the parameters of the project following the software’s developments after the completion of Clark’s work on pillar two. Computer simulations were conducted to exhibit the details of these progressions and to assist in familiarizing me with the status of the software. The information from these simulations enabled me to provide an initial round of guidance on further software development, and to begin considering hardware options for upcoming experiments.

1. Purpose

This phase began with the handover from the Clark, whose efforts were on pillar two. Continuing his research on AV’s SPOTR software, this phase consisted of processing

the SPOTR software data from past experiments in order to maintain momentum. With the information received during this phase, our main goal was to set the groundwork for continued progression of pillar two by providing AV with updated guidance for the software in reference to a SOF elements' needs in a rapidly developing MDO environment. After gaining an adequate understanding of the current state of the software and providing AV with our assessment, we shifted towards Phase I where we explored the possibilities of Blue sUAS drones to collaborate with AV's software.

2. Actions

Phase 0's methods consisted primarily of online meetings and simulations to demonstrate the current state of the SPOTR software. The meetings occurred primarily with AV on a weekly or biweekly basis through the phase II discovery experiments. Exploratory conversations were also begun with Anduril concerning their ability to design object detection software, or to adapt their existing software to achieve pillar two objectives.

3. Observations

The computer simulations demonstrated the theoretical limitations of the SPOTR software using a static and a moving drone over an urban area similar to the operational area present in the Middle East. The simulations revealed the quantity of stationary and mobile targets that the SPOTR software could identify simultaneously, along with the limits in its tracking ability as the targets moved by one another and behind obstacles such as buildings. The simulations revealed that the software would be able to detect humans, vehicles, and weapons under optimal conditions.

During approximately five months between the initial and latter stages of phase 0, AV achieved numerous advancements on their SPOTR software. The ability of the SPOTR software to integrate with a sUAS platform without requiring access the software and intellectual property of a sUAS was discerned during this time period. Perhaps most importantly, the SPOTR software's ability to identify objects at greater distances than those recorded five months prior was explained to be the result of both software improvements and more powerful cameras and processing capabilities.

The simulations revealed that the software's ability to maintain track of a particular human, vehicle, or weapon was extremely imprecise. During the simulations, a tracking number was given to each human, vehicle, and weapon that was identified. However, as the simulation continued to run, that tracking number changed every few seconds, making it impossible to maintain accountability of an entity through a tracking number without maintaining a constant visual of the entity of interest on a graphical user interface.

B. PHASE I: EQUIPMENT DOWN SELECT

In phase we assessed which Blue sUAS platforms could accommodate the SPOTR software to provide useable data and imagery for a SOF element. Figure 2 shows that the primary focus of this phase was selecting hardware and software for the project, with a substantial but less significant amount of effort placed towards refining the parameters. As knowledge and experience on the state of the project increased, due to additional experiments, demonstrations and simulations, so did the amount of guidance provided towards the software developers. Additional information on the capabilities and limitations of the software also enabled the opportunity to search for possible alternate routes of software development.

1. Purpose

Based on the results of phase 0, the goal of Phase 1 was to down select sUAS platforms that could best support the SPOTR software. The sUAS platform should assist in optimizing the SPOTR software performance when integrated with the sUAS during experimentation, and eventually in training scenarios and in an operational environment.

The FLIR (formally Altavian) M440, Skydio X2D, Vantage Vesper, Teal Golden Eagle, and the Parrot Anafi were the five sUASs originally selected as potential platforms for the SATLAS project. One critical attribute of the selected sUAS would be its ability to operate autonomously while supporting the SPOTR software to detect entities of interest. The autonomous function of the sUAS would be a key factor in limiting the cognitive workload of a SOF operator utilizing the sUAS while actively conducting a patrol.

2. Actions

The actions for phase I consisted of conducting virtual and in-person meetings with Anduril and DIU, and attending a live demonstration of an sUAS's capabilities for a DIU evaluation team.

After DIU's Blue sUAS program provided additional exploration and experimentation with the platforms that I was considering, I was able to narrow down which sUAS platforms could adequately perform to the project's required parameters. The specific sUAS that DIU designated as a Blue sUAS platform was selected for the discovery experiments in phase II.

The capabilities and limitations of the SPOTR software noticed during the simulations in Phase 0 led me to begin conversations with Anduril, another company known for creating object detection software for similar purposes. During our discussions, Anduril presented videos, simulations, and ongoing real life scenarios revealing the capabilities of their software, which exhibited more effective object detection at greater distances than AV's SPOTR software. Anduril's methods were centered around their organic products and lattice network system.

I was invited to observe pitches being conducted to DIU by varying sUAS vendors. The conversations with the vendors by DIU personnel covered battery life, durability, cost, levels of autonomy, and various other topics of value to the SATLAS project. The majority of the meetings that I attended included some discussions on the Skydio X2D (Figure 3).



Figure 3. Skydio X2D

The demonstration of the Skydio X2D was conducted at Fort Hunter-Liggett for DIU, members of SOCOM, visitors from the Pentagon, and other interested government agencies. The exhibition explained and demonstrated the X2D's size, weight, maximum flight time, max altitude, flight speed, and distance from the operator, along with its auto-return feature for when its limitations were reached. Some of the more advanced autonomous features covered during the demonstration were the X2D's ability to follow waypoints and programmed routes at predetermined altitudes, and speeds while taking videos and/or photographs. Similarly, the platform's ability to utilize its six cameras and sensors to avoid obstacles, making it resistant to crashes, were exhibited. The X2D's ability to autonomously conduct 3D mapping of a vehicle, which was also reported to be an option for certain buildings, was also demonstrated.

3. Observations

Both the conversations with DIU along with the demonstrations at Fort Hunter-Liggett suggested that from the currently available sUAS options, the Skydio X2D would be the optimal platform to support the SPOTR software. The camera utilized by the X2D is one of the more advanced cameras currently being used by US-made sUASs, providing the numbers of pixels through the visual metadata that would be necessary to enhance the

SPOTR software's ability to accurately detect, identify, and categorize entities of interest from greater distances.

The X2D exhibited some of the most sophisticated autonomous features seen in the Blue sUAS platforms. All manual and autonomous commands could be manipulated through the X2D controller shown in Figure 4. These autonomous features made the X2D extremely difficult to crash into stationary or mobile objects during daylight hours. For a SOF operator, these features would be key to easing the cognitive workload during an active patrol.



Figure 4. Skydio X2D Controller

Some X2D limitations that we observed during the demonstration were its auditory signature created by its propellers, its limited capabilities during lowlight hours, its inability to operate in inclement weather, and its inability to mask or disguise its RF signature. Regardless of the altitude at which the X2D was flown during the demonstrations, it could always be heard, even if it could not be seen. Reducing its acoustic signature would prove critical for maintaining operational security in denied terrain. During lowlight hours, the X2D's thermal camera is a useful feature. However, its obstacle avoidance is severely reduced as a result of similar heat signatures given off by inanimate

objects during lowlight hours. Skydio reported that they are actively working on waterproofing the X2D to enable its usability in a variety of weather conditions, but this capability is still in the developmental stage. The ability to turn off its RF emitter for operating in contested environments is also a necessity that has not currently been developed for the X2D.

C. PHASE II: DISCOVERY EXPERIMENT

Phase II included the discovery experiments during which the object detection software was integrated onto the technical Blue sUAS platforms. Figure 2 illustrates that phase II was the first phase during which experiments were the primary focus. The results of these experiments facilitated a greater amount of guidance on further research and development than in the previous two phases. Similarly, the performance of the hardware and software during these experiments enabled further refining of the parameters, but at a lesser extent than in the previous two phases.

1. Purpose

During this phase, the object detection software was utilized with three sUAS platforms to determine the feasibility of utilizing the platforms during SOF TTPs. In addition to the Skydio X2D covered in the previous section, the Altavian M440 and the Parrot Anafi were also tested during this phase of the experiment. A picture of the M440 is shown in Figure 5, and a picture of the Anafi is shown in Figure 6. Simple actions were conducted with the each sUAS platform to help determine the technical capabilities and limitations of the object detection software based off of each platform's individual features. The base level experiments drove the development of the hypothesis generating experiments of phase III.



Figure 5. FLIR (Altavian) M440



Figure 6. Parrot Anafi

2. Actions and Observations

Due to the more sophisticated nature of the discovery experiments, tables will be used to relay the specificities of each experiment. The first portions of these charts will cover the test purpose and objectives for this experiment in greater detail. The second portion of each test's chart will detail the set-up tasks, the concept, the sequence of events, and the schedule for that test. The observations will be covered at the end of each

experiment as opposed to at the end of this phase to help maintain continuity between the observations and their individual experiments.

a. Discovery Experiment I Methodology

Discovery Experiment I was focused primarily on successfully integrating the SPOTR software with the sUAS platforms of interest. Table 2 explains the test objective, technical requirements, research question, variables, and constraints. Table 3 describes the set-up tasks, the concept of the experiment, the sequence of events, and the timeline.

Table 2. SPOTR Software Integration Guidance

Short Title	SPOTR sUAS Integration
Test	I – Determine software’s compatibility with a sUAS platform
Test Objective	OBJ: Determine whether the SPOTR software can pair with the sUAS camera feed.
Technical Requirement	The software must successfully pair with a selected sUAS platform’s KLV full resolution video of varying sUAS platforms down to the ground with metadata. Pair: SPOTR software projects detected entities on active video feed from sUAS KLV: A data coding standard used to embed information into video feeds Down to the ground: Video feed is processed offboard and combined with the software present on the ground with the user
Research Questions	<i>RQ I-1. Can the SPOTR software integrate with a sUAS platform’s video feed?</i> <i>RQ I-2. Do the selected sUAS platforms need to be modified to enable pairing?</i> <i>RQ I-3. What equipment is needed to enable successful pairing?</i>
Independent Variables	IV. sUAS Platforms x3
Dependent Variables	DV. SPOTR Software
Constraints	1) The object recognition software must be remotely connected to the drone via a cable connection to a handheld controller or visual user interface platform to enable the SPOTR software access to the KLV full resolution video 2) Conduct 1–2 iterations each for test reliability, depending on time 3) All sUAS platforms being tested have been approved for experimentation by their respective originating organizations.

Table 3. SPOTR Software Integration Steps

Location	7625 Estrella Rd, Paso Robles	
Date	16 November 2021	
Setup Tasks	<p>Estimated duration: @ 20 minutes</p> <ul style="list-style-type: none"> Charge sUAS platform to be used for each iteration Charge handheld controller or visual interface platform for each iteration Identify connection points and compatibility of the cables for each sUAS and visual interface platform Activate SPOTR software 	
Concept	Determine if the SPOTR software can pair with each drone’s full motion video to facilitate object detection through the sUAS platform’s video feed	
Sequence	<p>Estimated duration: @ 25 minutes each</p> <p>Step 1. Connect Software to the appropriate drone Connect the SPOTR software to a specified sUAS platform using the appropriate cables Power on the sUAS to make sure that the platform and software are linked and compatible</p> <p>Step 2. Detect Entities Raise sUAS to a minimum of 10 meters altitude for initial detection of an entity using the sUAS platform’s organic camera</p> <p>Step 3. Repeat Conduct 2–3ea iterations as necessary Repeat for each platform</p>	
Schedule	Activity	NPS (PST)
	Test Set-up	08:30-08:50
	Conduct Test I	08:50–09:15

b. Discovery Experiment I Observations

For trial #1, the SPOTR software had no noticeable issues combining with the Parrot Anafi that AV had become accustomed to working with during their software development. Figure 7 shows the small, portable device containing the SPOTR software. Shortly after the SPOTR software was connected with the Anafi, the Anafi was raised to an altitude of approximately 10m where it immediately began detecting human and vehicle entities.

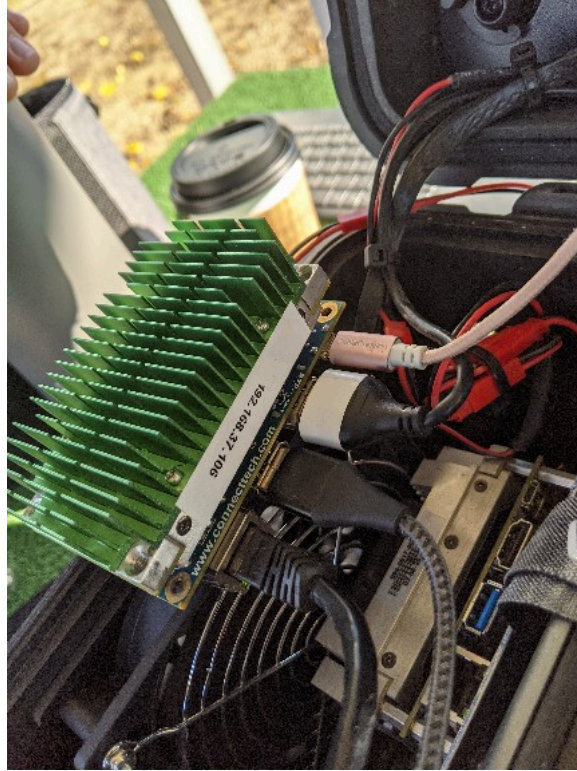


Figure 7. SPOTR Software Housing

During trial #2, the SPOTR software appeared to work with the Altavian M440 following its initial pairing, allowing the user to detect objects prior to the M440's take-off. The M440 exhibited issues when attempting to take-off due to the necessity of a specific application on the M440's user interface to initiate take-off. Once the application was appropriately manipulated to initiate the M440's take-off, the user experienced additional difficulties within seconds of maneuvering the M440 away from the user's position as a result of repeatedly losing connection to the link between the app and the M440 controller.

In trial #3, the Skydio X2D had issues connecting to the SPOTR software from the very beginning of the experiment. The experiment revealed that the X2D could record a video, and then after returning to the user, that video could be combined with the SPOTR software to reveal human and vehicle entities within the previously recorded video's feed. However, during this trial, the X2D's KLV metadata was not permitted to combine with the SPOTR software. Without the ability of the X2D's GPS coordinates or other location-

related data to send metadata directly to the SPOTR software, the sUAS was unable to provide orientation outside of visual orientation when combined with the SPOTR software.

c. Discovery Experiment II Methodology

Discovery Experiment II focused on conducting basic tasks with the sUAS while in flight to verify the functionality of the SPOTR software. Table 4 provides detailed objectives in a similar manner to Table 2. Table 5’s sequence of steps introduced the first SPOTR software capabilities and limitations experiments, providing an updated baseline for future experimentation.

Table 4. Initial Object Recognition Test Plan

Short Title	Initial Object Recognition Tests
Test	II – Discover SPOTR/Platform Performance Parameters
Test Objective	OBJ: Determine SPOTR/Platform effectiveness at differing ranges and angles
Technical Requirement	SPOTR software must detect an entity through the sUAS platform camera at minimum acceptable ranges and altitudes Range: horizontal distance from entity to the sUAS platform Altitude: vertical distance from the entity to the sUAS platform
Research Questions	<i>RQ II-1. What is the maximum range for the SPOTR software with each sUAS?</i> <i>RQ II-2. What is the maximum altitude for the SPOTR software with each sUAS?</i> <i>RQ II-3. Which sUAS provides the best results with the SPOTR software?</i> <i>RQ II-4. Which are the capabilities and limitations of each pairing?</i>
Independent Variables	IV-1. Entity proximity to sUAS(closer and farther) IV-2. Entity angle from sUAS IV-3. sUAS platform being used
Dependent Variables	DV. SPOTR Software Performance
Constraints	1) The object recognition software must be connected to the drone via a cable connection to the remote controller to access the KLV full resolution video 2) At least three individuals are needed for this experiment, one to fly the sUAS and monitor the video feed, one to serve as object for the SPOTR software to detect while managing the laser range-finder, and one to record the results of the experiment 3) Only one drone will be tested at a time to ensure accuracy due to the limited number of personnel conducting the experiment 4) Replications should be used in as similar of an environment as possible to eliminate external influencers

Table 5. SPOTR/Platform Performance Test Steps

Location	7625 Estrella Rd, Paso Robles	
Date	16 November 2021	
Setup Tasks	<p>Estimated duration: @ 5 minutes</p> <p>Ensure that at least 100m of open terrain is available for this experiment Verify software/platform pairing Place the laser range-finder at the start point of the experiment</p>	
Concept	<p>Determine the functionality of the software/platform at different ranges and altitudes to provide usable object detection that achieves the required performance parameters</p>	
Sequence	<p>Estimated duration: @ 55 minutes</p> <p>Step 1. Position Entities Place the entity manning the laser range-finder at the 0 meter start point Place the sUAS at the first 10 meter mark</p> <p>Step 2. Detect Entities Raise sUAS to a minimum of 10 meters altitude for initial detection Continue raising the sUAS platform until it reaches its maximum detection altitude and record each Move the sUAS platform to the 20 meter range mark and repeat the experiment by raising the sUAS platform to the max effective altitude of the SPOTR software Continue to repeat these steps until object detection software no longer successfully detects entities</p> <p>Step 3. Repeat Repeat for additional iterations as necessary</p>	
Schedule	Activity	NPS (PST)
	Test Set-up	09:15-09:20
	Conduct Test II	09:20-10:15

d. Discovery Experiment II Observations

The Parrot Anafi successfully conducted all exercises during this experiment. The Skydio X2D successfully conducted a portion of the exercises required for this experiment. Due to the complications experienced with the Altavian M440 during the initial experiment, the M440 was unable to perform any of the exercises during this round of experimentation.

During trial #1, the Anafi consistently detected both human and vehicle entities at the baseline 10 meter altitude out to a 50 meter distance where the detection became intermittent for both types of objects. At an altitude of 20 meters, the accurate detection of vehicles remained constant up to 75 meters, while the SPOTR software detection of human entities became intermittent at 60m. At 60m, human detection was consistent if the zoom feature of the Anafi was utilized. With the zoom feature activated, vehicle and human detection were consistent out to a distance of 96m at a 20m altitude for the Anafi. The maximum effective detection altitude for the Anafi while within a 50 meter range of the entity was 320 meters, at which point the human objects became intermittent.

In trial #2, the Skydio X2D yielded significantly less data as a result of issues with the metadata. Of note, the X2D full motion video when combined with the SPOTR software following a recording failed to recognize black vehicles. We believed this was a result of the software's mis-categorization of the black vehicle as a shadow. Detection of other vehicles was also intermittent depending upon the direction that the vehicles were facing. The X2D did have a more powerful zoom feature, which facilitated its ability to detect entities at a range exceeding 100m when utilized.

Other issues that were observed during the discovery experiments were the effects of obstacles, and instances of misidentification. During the second discovery experiment, the Anafi detected a human entity moving from one location to another. As the human entity crossed behind trailers and foliage, the tracking number to that individual changed, implying that the entity was a different individual each time that he appeared on the other side of an obstacle. Similarly, the SPOTR software misidentified horses as human targets when the horses were facing directly toward the sUAS. A few trailers were also misidentified as intermittent vehicles when the sUAS was in motion.

D. PHASE III: HYPOTHESIS GENERATING EXPERIMENTS

In phase III we conducted experiments in three differing terrains to provide a more in depth assessment of how the object detection software needed to be developed to meet the needs of a SOF element conducting MDO. Figure 2 demonstrates that the largest amount of experimentation took place in phase III. In accordance with a greater level of

experimentation, the largest amount of guidance was also provided during this phase. Minor adjustments on hardware selection and parameter refinement were also provided during this phase, primarily in reference to further experimentation.

1. Purpose

Phase III's purpose was to comprehensively evaluate the current capabilities and limitations of the SPOTR software when combined with a sUAS, through the execution of more detailed and thorough experimentation. The data collected during this phase facilitates the generation of hypotheses from which advancements and improvements in the SPOTR/sUAS system would most expeditiously enhance the system's capacity to augment a SOF element. The primary areas of focus during this phase were the maximum effective range and altitude of the system's object detection for both humans and vehicles. The system's performance in differing types of terrain, and its ability to track an entity both manually and while conducting autonomous actions were also examined during this phase.

2. Actions and Observations

The hypothesis generating phase includes the most complex experiments conducted during this project. This phase is divided into three trials or sets of experiments. The first experiment evaluated the maximum range and altitude of the SPOTR/sUAS. The second experiment examined the system's performance in differing terrain with varying obstacles. The last experiment concentrated on the system's performance during autonomous operations.

Due to the observations from the discovery experiments in phase II, only the Parrot Anafi and the Nibbler (an AV-specific sUAS used in previous iterations of SATLAS) were used during the hypothesis generating experiments. The Anafi was the only sUAS used during hypothesis generating experiments I and II, while the Nibbler was the only platform used during hypothesis generating experiment III.

a. Hypothesis Generating Experiment I Methodology

The first hypothesis generating experiment collected data on the maximum effective range and altitude of the SPOTR software and Anafi sUAS pair. Table 6 details

the difference between the detect, locate, and identify tasks for the SPOTR software for stationary and moving human and vehicle entities. Table 7 elaborates through step three of the iterations, illustrating the variety of trials being conducted in an effort to discover whether the complexity of the entity or its conduct affected the system’s performance.

Table 6. SPOTR/sUAS Maximum Range and Altitude Test Plan

Short Title	SPOTR Range and Altitude
Test	III – Determine maximum range and altitude in open terrain
Test Objective	OBJ: Determine the system’s maximum effective range to detect, locate, and identify an entity
Technical Requirement	The platform/software system must recognize an entity at sufficient standoff range to enable a SOF element to detect, locate, and identify an entity with a sufficient amount of reaction time Detect: Determine the presence of an entity Locate: Determine the grid coordinates and/or direction of movement by the entity Identify: Categorize between vehicle, human, or weapon
Research Questions	<i>RQ III-1. What is the maximum effective range to detect an entity?</i> <i>RQ III-2. What is the maximum effective altitude to detect an entity?</i> <i>RQ III-3. What is the maximum effective range to locate an entity?</i> <i>RQ III-4. What is the maximum effective altitude to locate an entity?</i> <i>RQ III-5. What is the maximum effective range to identify an entity?</i> <i>RQ III-6. What is the maximum effective altitude to identify an entity?</i>
Independent Variables	IV-1. sUAS range relative to stationary entity IV-2. sUAS range relative to moving entity IV-3. sUAS altitude relative to entity IV-4. Number of entities (single vs. multiple) IV-5. sUAS camera zoom feature (used vs. not used) IV-6. Entity location (gravel road vs. open field)
Dependent Variables	DV-1. Entity is detected/not detected (at a given range) (consistent vs. intermittent) DV-2. Entity is detected/not detected (at a given altitude) (consistent vs. intermittent) DV-3. Entity is located (at a given range) (consistent vs. intermittent) DV-4. Entity is located (at a given altitude) (consistent vs. intermittent) DV-5. Entity is identified (at a given range) (accuracy) DV-6. Entity is identified (at a given altitude) (accuracy)
Constraints	1) The object recognition software must be connected to the drone via a cable connection to the remote controller to access the KLV full resolution video 2) At least four individuals are needed for this experiment, one to fly the SUAS and monitor the video feed, two to serve as objects for the SPOTR software to detect while managing the laser range-finder, and one to record the results of the experiment 3) Only one drone will be tested at a time to ensure accuracy due to the limited number of personnel conducting the experiment 4) If multiple drones are used, replications should be used in as similar of an environment as possible to eliminate external influencers 5) Need less than or equal to 400m of open terrain

Table 7. SPOTR/sUAS Maximum Range and Altitude Steps

Location	900 Innovators Wy, Simi Valley, CA 93065	
Date	12 February 2022	
Setup Tasks	<p>Estimated duration: @ 5 minutes</p> <p>Position entities as required Place the laser range-finder at the 0m start point of the experiment Ensure operability of all equipment</p>	
Concept	Determine the max effective range and altitude of the SPOTR software/platform system in 10m increments.	
Sequence	<p>Estimated duration: @ 240 minutes</p> <p>Step 1. Position Entities Place the entity manning the laser range-finder Place the sUAS at the initial close range and altitude to verify functionality Position the sUAS beyond detection range (stationary or moving)</p> <p>Step 2. Detect, Locate, Identify Entities Position sUAS at an initial altitude of 10m and specified range Decrease range until entity is detected, record results Increase altitude by 10m increment at specified range Decrease range until entity is detected, record results Repeat until maximum range and altitude have been determined without using the zoom feature Repeat entire experiment until maximum range and altitude have been determined while using the zoom feature</p> <p>Step 3. Iterations 3a. Detect, locate, identify single stationary human 3b. Detect, locate, identify single stationary vehicle 3c. Detect, locate, identify multiple stationary humans 3d. Detect, locate, identify multiple stationary vehicles 3e. Detect, locate, identify single moving humans (moving toward, perpendicular, and away from sUAS) 3f. Detect, locate, identify single moving vehicles (moving toward, perpendicular, and away from sUAS) 3g. Detect, locate, identify multiple moving humans (moving toward, perpendicular, and away from sUAS) 3h. Detect, locate, identify multiple moving vehicles (moving toward, perpendicular, and away from sUAS)</p> <p>Step 4. Repeat Repeat Step 3 with all available sUAS to obtain accurate interpretation of each system's performance</p>	
Schedule	Activity	NPS (PST)
	Test Set-up	08:30 – 08:35
	Conduct Test III	08:35 – 12:35

b. Hypothesis Generating Experiment I Observations

During hypothesis generating experiment I we recorded the maximum effective range and altitude of the SPOTR/sUAS system for both humans and vehicles. During our test design, we expected the SPOTR software to sequentially detect, locate, and identify each entity over a matter of seconds. We unexpectedly observed that the system simultaneously detected, located, and identified entities. Each single data plot in the scatter plot in Figure 8 represents the range (x-axis) and altitude (y-axis) at which the entity was detected, located, and identified during the experiment. The differing colors in Figure 8 reveal the variation on where the entity was detected, or whether it was detected while using the zooming feature.

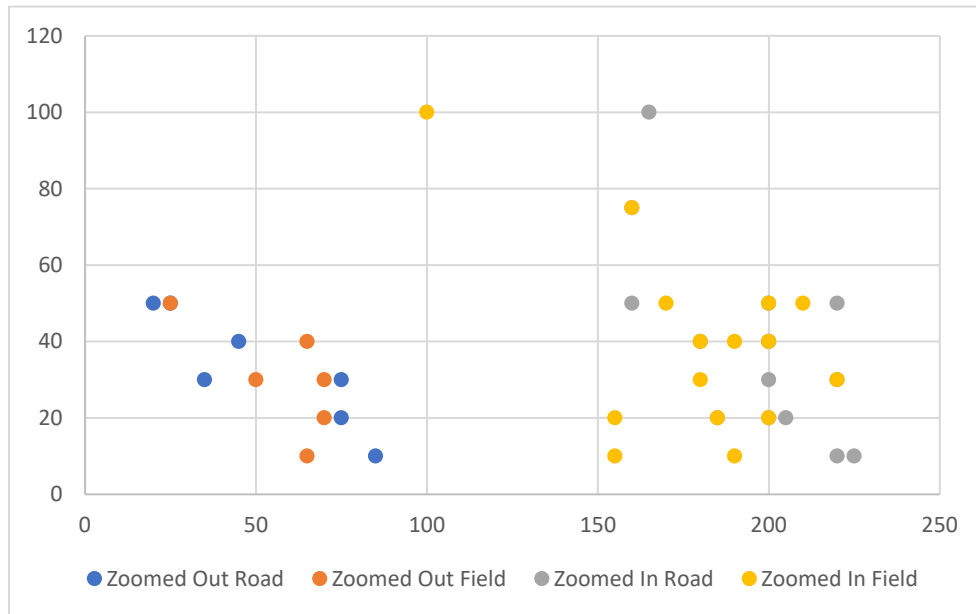


Figure 8. SPOTR/sUAS Human Detection Max Range and Altitude

At the time of hypothesis generating experiment I, the natural factor of wind at the testing site reached speeds of around 20mph. As a result, for the first two hours of the experiment the Parrot Anafi was not flown above an altitude of 50 meters. The data in Figure 8 exhibiting data collected above the 50 meters altitude was collected the following day when the wind was at a more manageable speed.

We assess that factors including the size of the human entity and the color of the clothing also affected the data. When conducting observations of multiple humans, we noticed on several occasions that the system more rapidly identified larger individuals at both closer and greater ranges and altitudes. When an entity wore a red jacket, it became more difficult for the object detection software to detect it, as opposed to when the entity was wearing a white or black shirt or jacket as shown in Figures 9 and 10 from the same range and altitude. Conversely, when an entity wore white or brightly colored hats as opposed to darker hats, the system detected it at greater ranges.



Figure 9. Undetected Entity with Red Jacket



Figure 10. Detected Entity without Red Jacket

As shown in Figure 8, although the differing ranges and altitudes were minimal, the system's ability to accurately detect a human entity was enhanced on a gravel road as opposed to in a field of green grass, both with and without using the zoom feature as demonstrated in Figures 11 and 12. The system detected entities both closer and farther from the sUAS while they were on a road. The system's ability to detect a human entity on the road at higher altitudes at close range, however, appears to have resulted from the system's misdiagnosis of the entity's shadow as a human as opposed to the entity itself (Figure 13). While zoomed in, the system's ability to detect an entity increased in altitude by at least 50 meters, and in range by nearly 150 meters.

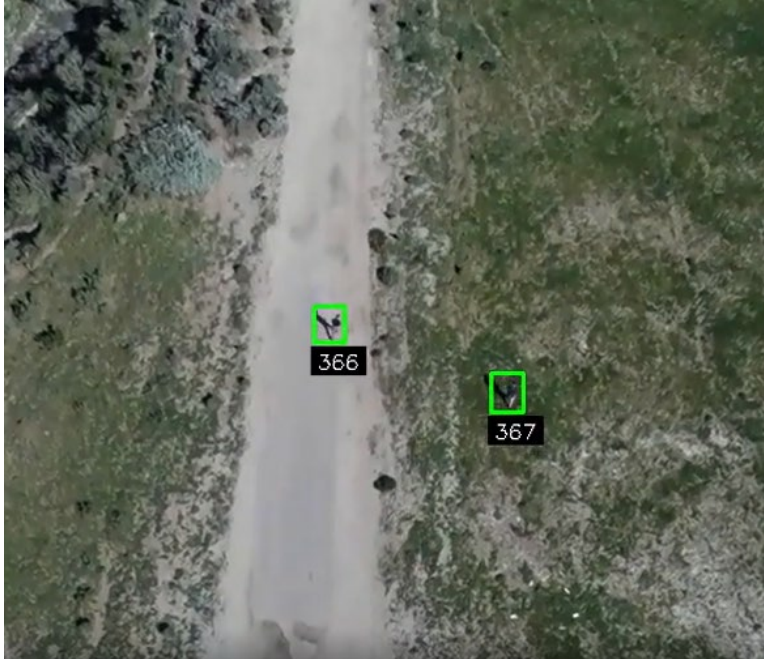


Figure 11. Detected Entities on both Road and Field



Figure 12. Detected Entity on Road and Undetected Entity in Field



Figure 13. Entity Shadow Misdiagnosis

There were no significant differences observed in the system's detection of a single human vs. multiple humans, or a moving human vs. a stationary human. Both single and multiple human entities' minimum and maximum ranges and altitudes while stationary or moving were nearly identical. Immediately after a human entity exceeded the system's detection range or altitude, the entity was directed to move perpendicular or parallel to the system in order to get the software to detect the entity. Despite these efforts, we observed that once an entity exceeded the range of the system, no movements resulted in the system's reacquisition of the entity.

Overall, the maximum range at which a human entity was detected using the SPOTR software paired with the Anafi sUAS was 225 meters. The maximum altitude at which a human entity was detected was 100m. When flying at 100 meters, however, its maximum range decreased by approximately 50 meters when zoomed in on the road, and by approximately 125 meters when zoomed in in a field. Similarly, when zoomed out on

the road and in the field, the range at which the system consistently detected a human decreased as the altitude increased as shown in Figure 8.

Throughout all hypothesis generating experiments, the segments focused on vehicle entities were restricted to the road. Figure 14 depicts a detected vehicular entity, while Figure 15 depicts an undetected vehicular entity. As indicated in Figure 16, the main discerning factors observed in the scatter plot were whether the entity was observed using the zoom feature, or without it. As with Figure 8, each dot in Figure 16 represents the range and altitude at which the vehicle was simultaneously detected, located, and identified.



Figure 14. Detected Vehicle Entity



Figure 15. Undetected Vehicle Entity

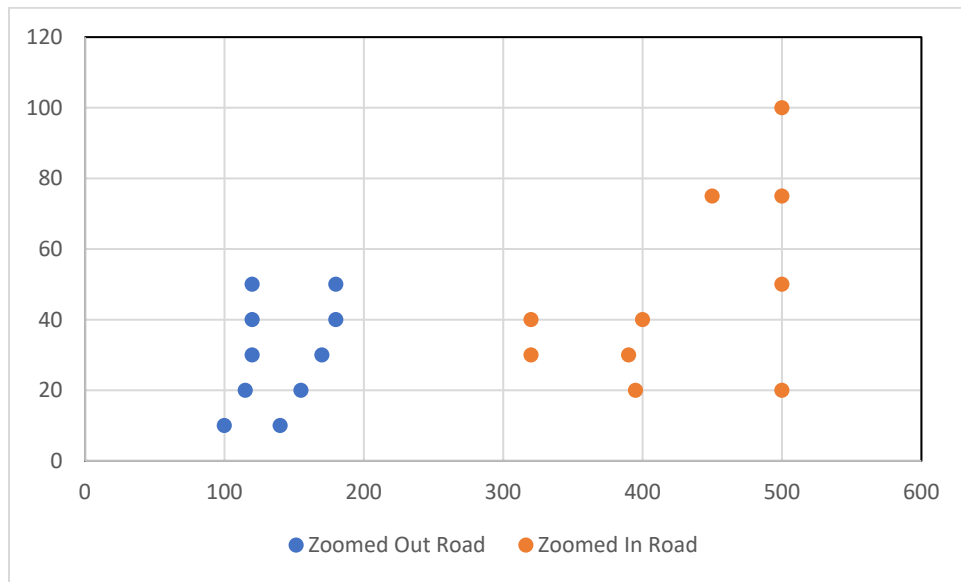


Figure 16. SPOTR/sUAS System Vehicle Detection Max Range and Altitude

In Figure 16, the system’s ability to detect a vehicle entity did not appear to decrease at higher altitudes as it did when detecting a human entity. At an altitude of 100m, while using the zoom feature, a vehicle was detected at the maximum range of approximately

500m. Conversely to the system's performance on human entities without the zoom feature, there was a slight increase in range with increased altitude as shown in Figure 16.

For the vehicular entities, when using the zoom feature, the maximum range was assessed to be 500m as shown in Figure 17, while the maximum altitude was assessed to be 100m. Without the zoom feature, the maximum range was assessed to be approximately 175 meters, and the maximum altitude was 50 meters. The data revealed an increase in range of approximately 325 meters and an increase in altitude of 50 meters when using the zoom feature.



Figure 17. Maximum Range of Vehicle Detection

c. Hypothesis Generating Experiment II Methodology

The second experiment for phase III was directed toward the SPOTR/sUAS system's ability to detect, identify, locate and track a human or vehicular entity in varying terrain. In addition to the open terrain utilized during the first experiment of phase III, urban and wooded terrain and their effects on the system's performance were assessed during this experiment. For urban terrain, we evaluated the effects of clear and tinted glass windows,

doorways, roof hatches, and simulated buildings. For wooded terrain, the effects of shadows, and thick or intermittent foliage were assessed. Table 8 provides the experimental variables and parameters, while Table 9 presents a detailed description of the set-up and sequence of iterations.

Table 8. SPOTR/sUAS System Performance in Varying Terrain Test Plan

Short Title	SPOTR Performance in Varying Terrain
Test	IV – Determine effects of wooded and urban terrain
Test Objective	OBJ: Determine the system’s capacity to detect, locate, identify, and track an entity while in wooded and urban terrain
Technical Requirement	The platform/software system must recognize an entity at sufficient distance to enable a SOF unit to detect, locate, identify, and track it with a sufficient amount of reaction time Detect: Determine the presence of an entity Locate: Determine the grid coordinates and/or direction of movement by the entity Identify: Categorize between vehicle, human, or weapon Track: Maintain positive accountability of an entity
Research Questions	<i>RQ IV-1. How do buildings affect the system’s ability to detect, locate, identify, or track an entity?</i> <i>RQ IV-2. How do stationary vehicles affect the system’s ability to detect, locate, identify, or track an entity?</i> <i>RQ IV-3. How do trees affect the system’s ability to detect, locate, identify, or track an entity?</i> <i>RQ IV-4. How do shadows affect the system’s ability to detect, locate, identify, or track an entity?</i> <i>RQ IV-5. What is the maximum effective range in urban terrain to detect, locate, identify, or track an entity?</i> <i>RQ IV-6. What is the maximum effective in wooded urban to detect, locate, identify, or track an entity?</i> <i>RQ IV-7. What is the maximum effective range in wooded terrain to detect, locate, identify, or track an entity?</i> <i>RQ IV-8. What is the maximum effective in wooded terrain to detect, locate, identify, or track an entity?</i>
Independent Variables	IV-1. sUAS range relative to stationary entity IV-2. sUAS range relative to moving entity IV-3. sUAS altitude relative to entity IV-4. Number of entities (single vs. multiple) IV-5. Type of obstacle concealing stationary or moving entity
Dependent Variables	DV-1. Entity is detected, located, identified, or tracked (at a given range) (in a given terrain) (consistent vs. intermittent) DV-2. Entity is detected, located, identified, or tracked (at a given altitude) (in a given terrain) (consistent vs. intermittent) DV-3. Entity is detected, located, identified, or tracked with obstacle (consistent vs. intermittent)

Constraints	<ol style="list-style-type: none"> 1) The object recognition software must be connected to the drone via a cable connection to the remote controller to access the KLV full resolution video. 2) At least four individuals are needed for this experiment, one to fly the SUAS and monitor the video feed, two to serve as objects for the SPOTR software to detect while managing the laser range-finder, and one to record the results of the experiment 3) Only one drone will be tested at a time to ensure accuracy due to the limited number of personnel conducting the experiment. 4) If multiple drones are used, replications should be used in as similar of an environment as possible to eliminate external influencers. 5) Need less than or equal to 500m of wooded and urban terrain
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Table 9. SPOTR/sUAS System Performance in Varying Terrain Steps

Location	900 Innovators Wy, Simi Valley, CA 93065
Date	12 February 2022
Setup Tasks	<p>Estimated duration: @ 5 minutes</p> <p>Position entities as required</p> <p>Place the laser range-finder at the 0m start point of the experiment</p>
Concept	<p>Determine the max effective range and altitude of the SPOTR software/platform system increments.</p> <p>Determine the effects of terrain obstacles on SPOTR software/platform performance.</p>
Sequence	<p>Estimated duration: @ 120 minutes</p> <p>Step 1. Position Entities</p> <p>Place the entity manning the laser range-finder</p> <p>Place the SUAS at the initial close range and altitude to verify functionality</p> <p>Position the SUAS beyond detection range (neither stationary or moving)</p> <p>Step 2. Detect, Locate, Identify Entities</p> <p>Position SUAS at an initial altitude of 10m and specified range</p> <p>Decrease range until entity is detected, record results</p> <p>Increase altitude by 10m increment</p> <p>Decrease range until entity is detected, record results</p> <p>Repeat until maximum range and altitude have been determined</p> <p>Position obstacle between entity and SPOTR/sUAS system</p> <p>Decrease range and altitude until entity is detected, record results</p> <p>Step 3. Iterations</p> <p>4a. Detect, locate, identify, track single stationary human</p> <p>4b. Detect, locate, identify, track single stationary vehicle</p> <p>4c. Detect, locate, identify, track multiple stationary humans</p> <p>4d. Detect, locate, identify, track multiple stationary vehicles</p> <p>4e. Detect, locate, identify, track single moving humans (moving toward, perpendicular, and away from sUAS)</p>

	<p>4f. Detect, locate, identify, track single moving vehicles (moving toward, perpendicular, and away from sUAS)</p> <p>4g. Detect, locate, identify, track multiple moving humans (moving toward, perpendicular, and away from sUAS)</p> <p>4h. Detect, locate, identify, track multiple moving vehicles (moving toward, perpendicular, and away from sUAS)</p> <p>Step 4. Repeat Repeat Step 3 with all available sUAS to obtain accurate interpretation of each system's performance</p>	
Schedule	Activity	NPS (PST)
	Test Set-up	14:00 – 14:05
	Conduct Test IV	14:05 – 16:05

d. Hypothesis Generating Experiment II Observations

During the second experiment of phase III, the SPOTR/sUAS's ability to detect and/or track entities in urban terrain experienced difficulties when an entity was behind glass, within a doorway, emerging from a roof hatch, or within the shadow of a building. Although human entities were easily seen behind both tinted and clear glass windows with the naked eye, the system failed to identify any entities regardless of range and altitude as shown in Figure 18. If an entity stood or sat within a glassless window opening, however, the system detected and maintained track of the entity at a range of approximately 10 meters, with an altitude of less than 20 meters as shown in Figure 19. When an entity stood within a narrow doorway, the system either failed to detect the entity as shown in Figure 20, or it detected them intermittently if the entity was detected prior to entering the doorway as shown in Figure 21. When half of a human entity was exposed through the top of a roof hatch as shown in Figures 22 and 23, the system failed to detect the entity as well. Similarly, when a human entered the shadow of a building, the system often failed to maintain track or detect that entity.



Figure 18. Entity behind Tinted Window



Figure 19. Entity in Glassless Window



Figure 20. Undetected Entity in Narrow Doorway



Figure 21. Detected Entity in Narrow Doorway



Figure 22. Entity Emerging from Hatch



Figure 23. Anafi Observing Entity in Hatch

With the stationary and moving vehicles in urban terrain, we tested the system's performance to identify multiple entities simultaneously. While the system identified SUVs, cars, and large trucks quickly, it intermittently identified school buses, and did not detect tractors or the cargo carrying trailer of transfer trucks as vehicular entities as shown in Figure 24. The results of detecting stationary and moving vehicles were the same. In open terrain, the software identified vehicles more accurately when the side profile of the vehicles were presented toward the sUAS. In the same way as with the human entities, once a vehicle entered a shadow of a building, the system either lost track of the vehicle or was unable to detect the vehicle if it was not already tracking it.



Figure 24. Vehicular Entity Variety

In wooded terrain, the system usually failed to detect or maintain track of human entities once they were within a tree's shadow or beneath its branches. There was one instance while using the zoom feature where a human entity was still maintained by the system after entering a shadow as long as the entity's legs and feet remained within the sunlight as shown in Figure 25. On another occasion on the second day of testing, after an update was conducted on the SPOTR software, the system maintained track of a human entity after it entered the shadow produced by a tree as long as the entity was wearing a white or brightly colored shirt and remained near the perimeter of the shadow. The software update failed to improve the system's ability to detect or continue tracking an entity after being concealed by the branches of a tree.



Figure 25. Entity Leg Detection in Tree Shadow

The system intermittently maintained track of an entity in shadows, manifesting similar issues as those observed during the urban experiments. Each time a shadow, building, vehicle, or something as thin as a light pole crossed between the sUAS and the entity that it was tracking, the entity would be assigned a new tracking number once reacquired. The tests also revealed that when a human entity emerged from a specific shadow within two seconds of a separate entity entering that same shadow, the emerging entity would be assigned the tracking number of the first entity that entered the shadow as shown in Figures 26 and 27. If the time period exceeded two seconds, the emerging entity would be assigned a different tracking number. The system consistently maintained track of vehicles in shadows in contrast to the system's ability to maintain track of humans within a shadow.



Figure 26. First Entity with Tracking Number 88 Entering Shadow



Figure 27. Second Entity with Tracking Number 88 Exiting Shadow

At times, issues with the link between the sUAS and the SPOTR software, or issues experienced from two entities being tracked within close proximity, revealed complications with the system's ability to maintain a consistent tracking number for a targeted entity. When the issues with the link took place, the track number assigned to the entity tended to jump by several numbers within a second. When entities being tracked were within a few meters of each other, on the other hand, the numbers assigned as a track to one entity or another tended to bounce back and forth between the two entities.

The system's max effective range and altitude to detect a human or vehicular entity within obstacle laden urban or wooded terrain was significantly less than in open terrain. The obstacles produced by buildings, windows, shadows, and foliage all disrupted the data points that the SPOTR software typically used to identify entities. The system did not exceed 20 meters altitude or 30 meters range when detecting an entity in the presence of the aforementioned obstacles. If an entity remained on a road with a clear line of sight to the sUAS, however, the software's range and altitude at which it could detect and track an entity were similar to the results observed in open terrain.

e. Hypothesis Generating Experiment III Methodology

We conducted the final experiment of phase III with the Nibbler sUAS to evaluate the SPOTR software's performance during autonomous activities. The Nibbler, shown in Figure 28, is a prototype designed and built by AV engineers. Due to time constraints, the Nibbler's autonomous activities were limited to following a designated entity. To enable this feature, an AV engineer selected an entity within the Nibbler camera's field of view, then selected the command to follow the selected entity. This last experiment was restricted to open terrain to limit the number of factors affecting the system's performance. Table 10 and Table 11 provide the objectives, variables, set-up, and sequence of events as presented in previous tables.



Figure 28. The Nibbler

Table 10. SPOTR/sUAS System Autonomous Tracking Test Plan

Short Title	SPOTR During Autonomous Operations
Test	V – Determine maximum range, altitude, and speed in autonomous tracking
Test Objective	OBJ: Determine the system’s maximum effective range, altitude, and speed to track a moving entity while using autonomous features
Technical Requirement	The platform/software pairing must consistently, autonomously maintain track of a moving entity at sufficient distance to enable a SOF element to observe, orient, decide, and act with sufficient reaction time while minimizing cognitive requirements Track: Maintain positive accountability of an entity
Research Questions	<i>RQ V-1. What is the maximum effective range to autonomously track an entity?</i> <i>RQ V-2. What is the maximum effective altitude to autonomously track an entity?</i> <i>RQ V-3. What is the maximum effective speed to autonomously track an entity?</i>
Independent Variables	IV-1. sUAS range relative to moving entity IV-2. sUAS altitude relative to moving entity IV-3. speed of sUAS IV-4. speed of entity
Dependent Variables	DV-1. Entity is autonomously tracked/not tracked (at a given range) (consistent vs. intermittent) DV-2. Entity is autonomously tracked/not tracked (at a given altitude) (consistent vs. intermittent) DV-3. Entity is autonomously tracked/not tracked (at a given speed) (consistent vs. intermittent)

Constraints	<ol style="list-style-type: none"> 1) The object recognition software must be connected to the drone via a cable connection to the remote controller to access the KLV full resolution video. 2) At least four individuals are needed for this experiment, one to fly the sUAS and monitor the video feed, two to serve as objects for the SPOTR software to detect while managing the laser range-finder, and one to record the results of the experiment 3) Only one drone will be tested at a time to ensure accuracy due to the limited number of personnel conducting the experiment. 4) If multiple drones are used, replications should be used in as similar of an environment as possible to eliminate external influencers. 5) Need less than or equal to 500m of open area
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Table 11. SPOTR/sUAS Autonomous Tracking Steps

Location	900 Innovators Wy, Simi Valley, CA 93065	
Date	13 February 2022	
Setup Tasks	<p>Estimated duration: @ 5 minutes</p> <p>Position entities as required Place the laser range-finder at the 0m start point of the experiment</p>	
Concept	Determine the max effective range and altitude of the SPOTR software/platform in 10 meter increments with each sUAS.	
Sequence	<p>Estimated duration: @ 120 minutes</p> <p>Step 1. Position Entities Place the entity manning the laser range-finder Launch the sUAS within range and altitude to detect, locate, identify, and track an entity</p> <p>Step 2. Detect, Locate, Identify, Track Entities Select the entity and a graphical user interface (GUI) Command the sUAS to track and follow the entity Gradually increase the speed of the entity until the sUAS loses track Increase altitude by 10m increment and repeat</p> <p>Step 3. Iterations 5a. Autonomously track single stationary vehicle 5b. Autonomously track and follow single moving vehicle</p> <p>Step 4. Repeat Repeat Step 3 with all available sUAS to obtain accurate interpretation of each system's performance</p>	
Schedule	Activity	NPS (PST)
	Test Set-up	08:30 – 08:35
	Conduct Test V	08:35 – 10:35

f. Hypothesis Generating Experiment III Observations

While conducting autonomous activities, the SPOTR/Nibbler pairing consistently identified other vehicles within its camera's field of view as shown in Figure 29. When the vehicular entities were identified, the SPOTR software was programmed to show the vehicle's orientation. The faint green arrow superimposed over the vehicles in Figures 29 and 30 illustrates this concept. Due to a previous configuration of the Nibbler to follow an autonomous robot in a separate experiment to enhance the robot's awareness of its surroundings, the Nibbler hovered no more than 25m above its entity of focus, and no more than 10m behind it while tracking it as illustrated in Figure 31. Hovering at this altitude and this range allowed the camera of the Nibbler to reach the quality necessary to successfully maintain track of the entity of focus.



Figure 29. Entities Identified During Autonomous Operations



Figure 30. Vehicular Entity Direction of Travel



Figure 31. Nibbler Autonomously Following an Entity

Once an entity was selected within the Nibbler's field of view and the command to follow the entity was given, the Nibbler immediately assumed its position slightly above it. The Nibbler consistently tracked a vehicular entity driving at speeds of up to 15mph, becoming intermittent at speeds of 18–20mph. If the Nibbler lost track of an entity due to excessive speed or maneuvers that brought the vehicle out of its field of view too quickly, the vehicle would have to be manually reacquired and selected to facilitate the follow command execution once again.

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IV. ANALYSIS

In this section, I analyze the results of Chapter III by phase. The expected and unexpected hindrances encountered during the actions of each phase will be addressed. The details behind what was observed during each phase will be explained, and the implications of the results of each phase will be clarified.

A. PHASE 0

During the first two objectives of Phase 0 as depicted in Table 1, we observed that the SPOTR software performance rapidly declined after exceeding a 20 meter distance from an entity as shown in Figure 32. Since the average maximum effective range of most small arms weapons is approximately 400 meters, a SPOTR/sUAS system that has a 20 meter range of detection will not increase the FP and SA of a SOF element in contested or denied territory. For this reason, the third objective of Phase 0: providing guidance for further development of the software, was a critical task for this phase.

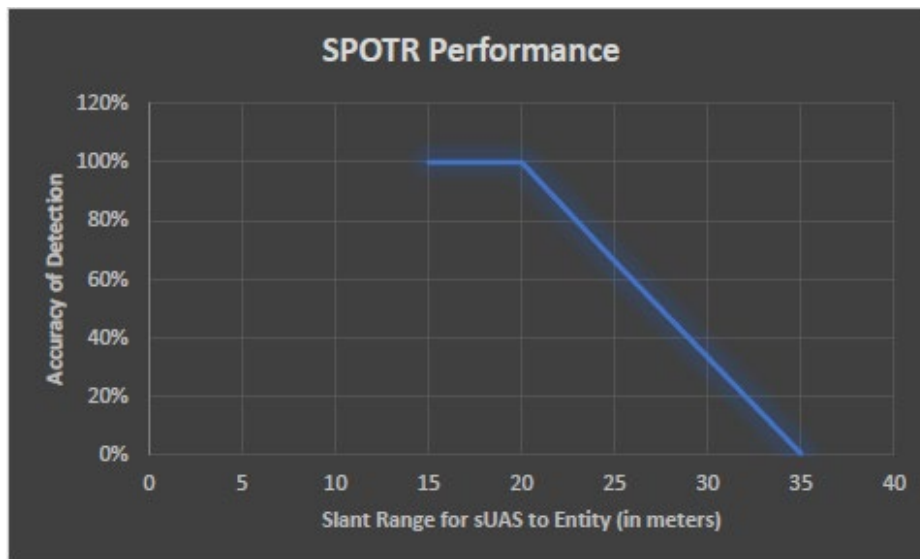


Figure 32. SPOTR Performance in Summer 2021⁷⁴

⁷⁴ Source: Clark, "Object Recognition in Support of SOF Operations."

During meetings conducted as part of Phase 0, we discussed that changing the camera and processing power of the SPOTR/sUAS pairing would increase the detection range of the software; however, it was clear to all participants that much more than hardware adjustments would be needed. After speaking with other technological companies who were also developing objection recognition software, it became apparent that what the SPOTR software needed was hundreds if not thousands of images of the objects that it would be detecting. The rapid rate at which this was being conducted hit somewhat of a speed bump when SPOTR's developers were acquired by AeroVironment.

1. AeroVironment Acquiring Progeny Solutions

When Progeny Solutions, the original creators of the SPOTR software, were acquired by the much larger AeroVironment (AV) near the end of Clark's research, it was unclear as to whether the project would be able to continue in the same manner as at its inception. With AV's differing objectives and goals for Progeny, we were uncertain where and how NPS and SATLAS would continue to fit in. The original goals of the SATLAS project, which were focused on NPS designed solutions to the sUAS problem for SOF elements, had to be adjusted. This development, along with the lack of computer, electrical, and software engineers at NPS to support our project, shifted an enormous level of responsibility for the project to AV's engineers and their ability to enhance the SPOTR software's performance. However, despite the limited focus, time, and money that AV's engineers could put toward object detection software, similar desires from other customers that AV was already working with made the rapid advancement of the SPOTR software much more of a reality.

2. Intellectual Property

A significant development from AV's work with respect to the SPOTR software was its ability to be processed offboard of a sUAS. The leading private sector sUAS companies hesitated to permit AV's access to the intellectual property codes within their sUAS platforms. Our original goal of conducting onboard processing of the SPOTR software, ran into numerous obstacles due to the need to integrate one company's software with a separate company's sUAS.

The understandable conflict of competing commercial sector companies withholding information and resources from one another, despite their common goal, was initially unavoidable. AV's shift in its R&D approach to process the software without accessing the internal wiring of the sUAS platforms of other companies was therefore invaluable. Although issues with the link between the sUAS camera feed to the SPOTR software experienced in phase III's hypothesis generating experiments reclarified the value of onboard processing, for the time being, the workable solution that AV created was the only way to continue our research. Unless one company became the sole producer of both the software and hardware, processing the data from the camera offboard was the only way ahead.

B. PHASE I

One of the most consistent responses by the AV engineers to requests for increased effective range for the SPOTR software, was to select a sUAS platform with a powerful camera that the SPOTR software could integrate with. For this reason, the first objective of Phase 1 as depicted in Table 1, selecting a Blue sUAS for further experimentation with SATLAS, was the primary objective for this phase. We leveraged the extensive work and expertise conducted by DIU on other sUAS platforms to help narrow down our choices. Phase 1's second objective, searching for ways to expedite the object detection software, was primarily directed toward Anduril, a company that already had prior experience and success working with SOCOM in similar pursuits.

1. Down-Selecting a SUAS Platform

At the beginning of Phase 1, we had a limited amount of sUAS options to experiment with. The only sUAS that we initially had readily available was the FLIR M440. We maintained M440s on campus and sent two M440s to AV to work with while developing their SPOTR software. In addition to the M440, AV had their own organic drone prototype Nibbler, and Parrot Anafis to integrate with their software. It was the affordability, familiarity, and ease of access that drove the use of these three platforms throughout Phases II and III. DIU's analysis and the live demonstrations, however, drove our decision to acquire the Skydio X2D to integrate with the SPOTR software. From the

highlights that DIU discussed, including autonomous behaviors, durability, and its ease of use, we decided that the X2D was our best option.

The ability of the X2D to autonomously conduct 3D mapping of a vehicle, building, or building interior was an impressive feature. The 3D mapping of a vehicle was shown during the live demonstration for DIU. The platform took several minutes to create a 3D map of a vehicle, implying that the time necessary to conduct a 3D map of a much larger building or the interior of a building would exceed the battery life of one platform. If this task were to be accomplished on a mockup of an average sized compound that a SOF element intended to raid, three or more platforms would be needed to conduct the mapping in a timely manner. This is under the assumption that the data from three platforms operating in support of each other could readily be assembled to create the 3D model desired, since this feat was not exhibited during the live demonstration for DIU.

The obstacle avoidance feature, which was accomplished through sensors placed along the perimeter of the X2D, was an important autonomous feature needed to facilitate rapid fielding at the earliest opportunity. In an environment where more than one person, if not an entire SOF element would need to be capable of operating the sUAS, the ability to easily and quickly operate or learn its capabilities and limits without destroying it would be critical.

A critical component of the X2D in the terms of its ability to integrate with the SPOTR software, would be its powerful camera. The X2D's camera's ability to perform a 16x digital zoom enhanced the SPOTR software's performance at greater ranges as indicated during phase II.⁷⁵ For these reasons, we selected the Skydio X2D as the preferred platform for the SPOTR software to combine with.

2. X2D Tactical Performance in MDO

Although the X2D exceeds the capabilities of what SOF teams currently operating with, there are still areas in which improvements need to be made prior to a SOF element using the platform in a MDO environment. Those areas include its RF and acoustic

⁷⁵ Skydio, "Defense Drones – Skydio Inc.," Skydio, 2022, <https://www.skydio.com/defense>.

signature, its lack of weather resistance, battery life, and its performance in limited light conditions.

A critical SOF consideration to tactically operate in an MDO environment is operational security. At the time of the demonstration in the summer of 2021, the X2D was not capable of operating without emitting an RF signature due the need to maintain track of its current position as well as the position of its operator. In an environment where a SOF element may be suspected, an RF signature from an American-made sUAS would serve as a beacon to the element's location.

Conversely, Anduril's Ghost platform is capable of operating without emitting an RF signature, but only during autonomous activities during which the operator will be unable track the platform's performance or progress. This fails to meet our goal of augmenting a SOF element that is actively on patrol. For that reason, perhaps discovering a way to mask or disguise the RF signature of the X2D would provide immense value to its feasibility in a denied environment.

Along the same lines, the auditory signature of the X2D was louder than the signature of the M440, the Anafi, the Nibbler, or any other sUAS that we worked with. This is understandable due to the X2D's power and speed. However, if it will be used in a denied environment, it would have to be flown at altitudes where it could not be heard or seen, offset from the SOF element by several hundred meters. For a SOF element operating in an urban or wooded AO, the usefulness of the platform would be lost at those altitudes and ranges. For this reason, a SOF element would have to restrict its use to open terrain during operations in denied terrain. Even in that situation, the platform would have to be much quieter when returning to the SOF element, or free fall to keep from completely compromising the element with its loud auditory signature.

The Skydio engineers who demonstrated the X2D's capabilities during the live demonstration explained that the X2D is not currently resistant to adverse weather conditions. If a SOF element is operating anywhere other than arid climates, this would greatly limit its useability. From the monsoon seasons of South America and Southeast Asia, to the arctic climates of portions of Europe and Asia, the X2D would frequently be

unusable. The Engineers at Skydio did state that they are currently working on waterproofing the X2D, and a working prototype should be available in the near future.

The battery life of the X2D is impressive in comparison to similar sUASs. However, certain SOF elements are often actively on patrol for several hours if not several days at a time. Although a sUAS with the capability to last for several days is not yet feasible, if one could last a few hours at the least, it would prove much more useful to an operating SOF element, preventing the need to return to base prematurely for additional batteries for extended operations. If this operating capacity were a reality, a SOF element could launch the platform from its base for KLEs or limited patrols, only retrieving it after they returned to the base. This would allow the platform to provide constant updates and SA throughout the duration of the patrol, mitigating and preventing situations similar to what was described in the vignette in Chapter II.

The last major area of concern for the X2D is its capabilities in limited light conditions. Although the X2D does have thermal cameras to assist navigation during limited light conditions, it loses its impressive obstacle avoidance after daylight hours. In the same way, the zoom feature of the X2D during night operations, while still impressive at an 8x zoom, is severely reduced in comparison to the 16x zoom exhibited during daytime operations. Since most SOF elements occasionally operate during low-light conditions, the X2D's limited performance in these conditions increases a SOF element's cognitive workload. The opposite of this scenario is the preferred outcome.

3. Anduril Potential

If SATLAS were to work with only one company, however, it would have been Anduril. Anduril's lattice network and its ability to detect and identify entities at great distances moving at great speeds, far outperformed anything that we worked with up to that point. However, we temporarily halted our investigation of potentially cooperating with Anduril due to their unwillingness to make sUASs due to market saturation. Anduril did express a willingness to work with Skydio and their X2D platform, but there have been no significant developments in this line of effort.

If Anduril does decide to cooperate with Skydio, we recommend facilitating another line of effort focused on their lattice system since preparing and deploying the massive antenna necessary for the lattice network to function in denied territories would be a major undertaking. In practical terms, a SOF element operating in a MDO environment would be too small to continuously transport or conceal an antenna of that size for an extended period of time. Therefore, the best applicability for a line of effort with Anduril may be during joint operations that are not being conducted in the deep fires area.

C. PHASE II

Despite the enthusiasm for the Skydio X2D and its various capabilities, the platform had to work with the SPOTR software for it to truly provide any value for the SATLAS project. This is what guided objective 1 of Phase II: integrating the Blue sUAS platforms with the SPOTR software. In the event that the Skydio X2D was not compatible with the software for one reason or another, the FLIR M440 and the Parrot Anafi were also tested during this phase as secondary and alternate options through which progress could continue to be made with the software until the X2D had been modified enough to facilitate its compatibility in future experiments. The second objective of Phase II, testing the SPOTR software with the sUAS platforms in minor experiments, was designed to set the stage for further experimentation. This objective helped to determine which platforms would be best for further experimentation in the immediate future, in order to provide the most value in determining the limits of the SPOTR software.

1. Barriers Preventing Further M440 and X2D Experimentation

As clarified in the previous section, the M440 and the Anafi were chosen for the discovery experiments mostly as matters of convenience, while the X2D was chosen as a preferred prototype for this phase of research. The M440 was tested due to the extensive amount of work conducted with this platform with the most recent preceding iteration of SATLAS. The Anafi was utilized due to AV's familiarity with this platform during previous tests with its SPOTR software over the last few months.

SPOTR integration with each platform was relatively straightforward. If the sUAS platforms and the laptop being used to facilitate the pairing were charged, and the cable

necessary to connect the software to the platform controllers was properly configured, the connection could be made relatively quickly. A generator was brought to the testing site to facilitate a continuous source of power throughout the experiments, eliminating the need for nearby hardstand structures or power sources. This is a must for future experiments at testing sites, which are typically far from hardstand structures and their associated power sources.

Once the experiment that tested for compatibility was underway, three separate friction points became evident: connectivity issues, outdated firmware and hardware, and insurmountable KLV processing hurdles. The connection issues were solved relatively quickly by identifying the appropriate cords and connection points to facilitate the pairing of the software with the M440 and X2D platforms. Once the connection points were properly configured, the issues with the SPOTR/sUAS compatibility transferred to firmware, battery, and controller updates for the M440, and permissions to access the KLV metadata through a digital stream of full motion video for the X2D.

The parent organizations of both of these platforms were contacted following these discovery experiments to assist in rectifying the situation. FLIR coordinated with us and AV for updating the batteries, controller, and firmware. However, the timeline necessary for these updates took over three months due to funding issues which delayed shipping on all ends. For this reason, the M440 did not receive the necessary updates prior to the conclusion of this phase of SATLAS, preventing any further tests on this platform.

In the same way, when contacted by NPS and AV concerning the issues with the KLV metadata, Skydio's engineers stated that the answer to rectifying the aforementioned issues would take several months. Skydio had already been contacted by similar organizations, including DIU, concerning the KLV issue. Whether the X2D is able to work with AV, or Anduril in a less likely but potentially also profitable scenario, making the KLV metadata accessible is an unavoidable improvement that Skydio must complete first. Since the estimated timeline of completion for these modifications to Skydio's system were projected to take place following the completion of this thesis, the X2D's contributions for the time being ended in the discovery experiments.

2. X2D and Anafi Discoveries

Despite the complications experienced with the X2D, it did reveal the capability to record videos which could later be integrated with the SPOTR software. During one of these videos, the X2D identified entities at greater ranges than the Anafi during the discovery experiments, as expected. In the event that the X2D is operating in a denied environment where RF signatures could not be emitted, requiring it to run an autonomous route without connections to the user in a similar way to Anduril's Ghost platform, could prove quite useful for reconnaissance missions. The missions would have to be conducted at high altitudes with the zoom feature enabled to facilitate the appropriate stand-off necessary to prevent compromise due to the auditory signature.

Another interesting finding for the X2D during its limited experimentation, was the SPOTR software's inability to recognize black vehicles when integrated with the X2D. Since the SPOTR/Anafi pairing falsely identified human shadows as human entities in the hypothesis generating phase a few months following this experiment, it's fair to assume that the X2D could have successfully identified black vehicles following a few months of updates to the SPOTR software. If the software required to identify humans is vastly different from the software needed to identify vehicles due to a larger number of humans in black clothing as opposed to black or darker colored vehicles in the software's programming, however, further developments of the software could still be needed.

The Anafi provided a lot more useful data during the discovery experiments. One contribution was its ability to demonstrate how optimal SPOTR/sUAS angles govern system position while observing an entity. The Anafi revealed a higher success rate of identifying entities at greater ranges when at higher altitudes. Just a 10m rise in altitude increased the range of the SPOTR/Anafi system by 25m. When the zoom feature was used, the range increased by over 30m when the altitude increased by 10m.

This data could prove useful for determining the optimal slant angle for a platform in the event that it detects entities on a planned route. If the the system is flown at an altitude and range that provides the optimal angle for detection, it greatly increases the effectiveness of the system as a whole.

D. PHASE III

After assessing that the Parrot Anafi was the only platform that worked well enough with the SPOTR software to conduct testing during the hypothesis generating experiments, the first objective of Phase III shifted to testing the limits and capabilities of the SPOTR/Anafi sUAS pairing. The limits and capabilities of the system were oriented around maximum effective range and altitude in open terrain, and the effects of the obstacles in urban and wooded terrain on the SPOTR software's ability to detect entities. The second objective of Phase III, testing the system during autonomous activity, was conducted solely with AV's Nibbler sUAS due to its autonomous capabilities which were not present within the Anafi. Due to time restraints, the autonomous tests were restricted purely to the Nibbler's ability to detect and identify other entities while conducting the autonomous task of following a designated entity.

1. Maximum Effective Range and Altitude

The results of the maximum effective range and altitude of the SPOTR/sUAS system were limited by only having the Parrot Anafi as an option. The limits of the Anafi platform's performance parameters, both in its ability to fly at certain altitudes and ranges, as well as in its camera's ability to detect entities with and without the zoom feature, served as the only data points through which to evaluate the system's maximum effective range and altitude. If the hypothesis generating experiments are repeated with the FLIR M440 or the Skydio X2D, the results of the tests will likely be significantly different than the data presented in this thesis. For those reasons, the data within this thesis should be used primarily as a reference to facilitate a better understanding on how the SPOTR software will perform on differing sUAS platforms with higher performing motors and camera systems.

a. Variables and Non-Factors

The original intent of the maximum range and altitude experiments was to conduct several subtests to determine how the system detected, located, and identified an entity at differing ranges and altitudes. The six separate dependent variables within Table 6 depict this expectation and its associated evaluation parameters. However, after discovering that

the SPOTR software simultaneously detected, located, and identified an entity, several subtests were combined into one.

As shown by the independent variables in the same table, we expected significant differences between whether an entity was stationary or moving, whether there was only one or two entities, whether the entity was detected on a road or within the more diverse background of a grass field, and whether the zoom feature was used or not used. Although our performance expectations for varied backgrounds with and without the zoom feature were correct, the effects of stationary or mobile targets along with the effects of single or multiple entities were unnoticeable. It is very likely that in a separate scenario where five or more entities are assessed, the performance may vary. Figure 33 illustrates this concept in the system's successful identification of only two vehicles out of a possible eight in the hypothesis generating experiments' urban terrain simulation. Similarly, if an environment that facilitates the movement of vehicles at higher rates of speed in varying directions were to present itself, it is likely that these variables would affect the system's performance.



Figure 33. Limited Detection with Multiple Vehicle Entity Options

Since it was determined that neither the number of entities, nor their stationary or moving status affected the systems' performance, these factors were not noted in Figure 8 or Figure 16. Similarly, since the detect, locate, and identify features were all indistinguishable, they were not noted on Figure 8 or Figure 16.

b. Environmental Factors and Non-Factors

An additional factor to take into consideration for the primary maximum effective range and altitude experiments, is the environmental factors. Due to limited funding and opportunities, the experiments were conducted only within the rolling hills of central and southern California. The system was not tested in any stressful environments in the form of extreme heat or cold, nor were the platforms capable of being tested in more tropical environments where rain is a consistent factor. If these experiments are repeated within the aforementioned environments, the natural influencing factors will likely affect the maximum effective range and altitude of the system.

One natural factor during the hypothesis generating experiments, however, was high winds. As stated within Chapter III of this thesis, the winds during the first day of testing for this phase of experimentation reached upwards of 20 miles per hour. For this reason, although the Anafi was able to reach altitudes of over 300 meters during the discovery experiments, it was not raised above 50 meters for the first part of the hypothesis generating experiments. As the winds began to calm down later in the day, the Anafi was raised to 100 meters as its maximum altitude. Time constraints prevented any testing from being conducted at altitudes higher than 100 meters.

The last environmental factor that was not able to be observed was its performance in limited light conditions. Although we previously planned to conduct experiments during dusk on the first day of experimentation, an unexpected visit from the CEO and other members of AV's executive staff caused the limited visibility experiments to be cancelled. Due to the lower levels of clarity with thermal cameras, and the limited number of images uploaded for the SPOTR software to process in reference to entities in limited light scenarios, it can be assumed that the maximum effective range and altitude of the system would significantly decrease in lower light conditions.

c. Human Detection

The original sequence for evaluating the system's performance for detecting human entities directed the entities being observed to carry the laser range-finder while the drone continued to move farther distances from the entity, as described in Table 7. Due to the

heavy wind conditions, however, the recorder maintained the laser range finder, while the entity continued to move farther from the sUAS system. This practice could prove beneficial in future experiments due to the larger frame of a human entity, making it much easier to designate an entity with the laser range finder.

As discussed in Chapter III, an individual's height and clothing affected the system's performance. Therefore, an additional factor to consider when preparing to program the SPOTR software for a particular area of interest, is to ensure that the images being uploaded into the system consist of individuals of the height, clothing style, and clothing color of the target individuals in the area of operation if possible. When the system more readily detected taller and broader individuals, it is possibly a result of simply having a larger mass for the system to detect. However, AV's engineers stated that the system's more rapid acquiring of certain entities could also be due to the possibility that the majority of the images used to train the system were of that specific individual. The images used to train the system were also used to explain the system's more rapid acquirement of entities wearing black shirts, as opposed to entities wearing red shirts and jackets, which are much more readily detected with the human eye.

The data in Figure 8 reveals that the contrast of a human entity on a road is slightly more easily detected by the system as opposed to an entity in a grass field, both with and without the zoom feature. For this reason, it can be expected that in most operational environments where the background produces varying levels of contrast, preventing an entity from standing out, the system's performance will be slightly reduced.

It was also apparent that when detecting human entities in the hypothesis generating experiments, higher altitude did not necessarily equate to greater range as it did during the discovery experiments. As depicted in Figure 8, we assess the maximum effective altitude of the Anafi for detecting a human entity in open terrain to be approximately 50 meters, even though the tests reached altitudes of 100 meters. At this maximum effective altitude, a maximum effective range of up to 225 meters was achieved by the system. At altitudes of 75 and 100 meters, the range of the system dropped by either 50 or 125 meters depending on whether the entity was on the road or within a field.

Similarly, while not using the zoom feature, the maximum effective altitude was assessed to be approximately 30 meters. At this maximum effective altitude, the maximum effective range of the SPOTR/Anafi system was approximately 75 meters. As the system was raised to 40 and 50 meters of altitude, the range decreased by 25–50 meters. This data, along with the data in the previous paragraph, helps to describe what may be the optimal angle for observing human entities in open terrain with the Parrot Anafi.

d. Vehicle Detection

The manner in which the vehicles were detected resembled the human detection in some ways, while differing in others. The same techniques used to evaluate the range and distance of the human entities were used to evaluate the range and distance of the vehicle entities. The recorder with the laser range-finder remained in vicinity of the system while the vehicles increased their distances from the system to obtain the maximum range and altitude information. The tests differed from the human entity detection primarily due to rougher terrain. The terrain in the testing area justified keeping the vehicles on the road. For that reason, the data in Figure 16 only depicts the vehicles as entities that were detected either with or without the zoom feature.

One factor that became evident with the vehicles that was not apparent with the human entities was the system's detection based off of the direction that the vehicular entities were facing. To verify this, at one point when a vehicle had exceeded its maximum detection range while facing the sUAS, the vehicle was turned to expose its side to the system, allowing the SPOTR software to reacquire the vehicle without decreasing the range between the entity and the system. Unfortunately, time and the terrain of the testing sites did not permit an opportunity to conduct further tests of a vehicular entity at greater distances from the system with the entity's broad side continuously being exposed to the camera of the sUAS platform. We deduce that the recorded maximum ranges and altitudes displayed in Figure 16 would be greater when observing the side of a vehicular entity.

Another factor noticed when observing the vehicles was how the altitude did not appear to affect the maximum range of detection as noticed with the human entity experiment. This observation implies that the factual maximum range and altitude of the

system when observing a vehicular entity was not actually reached. It is likely that the terrain at the 500-meter mark may have played a greater role in causing the SPOTR/sUAS system to fail in its detection as opposed to the distance from the system itself, as was the case with the human entities. Figure 34 illustrates how the exposure of the rear of the entity to the sUAS, in comparison to the broadside of the entity as displayed in Figure 17, possibly resulted in what was recorded to be the maximum range of object detection for vehicular entities. If time permitted, additional tests would have been conducted at different sites where terrain provided less restrictions to the vehicular path in order to assess whether the vehicle maximum range could in fact exceed 500 meters, and whether the maximum altitude could exceed 100 meters. A similar breakdown of the data, where at certain altitudes the range begins to decrease, would be expected if the maximum ranges and altitudes were retested in more open terrain.



Figure 34. Vehicle Entity Change in Exposed Surface at Maximum Range

However, based off of the data presented in Figure 16, the maximum altitude and range of the SPOTR/Anafi system while using the zoom feature on vehicles are 100 meters high, and 500 meters in distance respectively. While observing a vehicular entity without the zoom feature, the maximum effective range for the SPOTR/Anafi system was approximately 175 meters, while the maximum effective altitude was 50 meters.

2. Urban and Wooded Terrain Effects

The second hypothesis generating experiment focused on the varying effects of wooded and urban terrain on the SPOTR/sUAS system's ability to detect and track entities.

During this experiment, we observed that the entities while in wooded or urban terrain maintained similar maximum range and altitude data as observed in open terrain if their frames remained visually unobstructed or unaltered by obstacles. When an obstacle being used to simulate urban terrain or wooded terrain did obstruct the system's ability to visually acquire an entity, or if an obstacle obstructed an entity's frame, the range and altitude needed for the system to properly detect or track the entity was usually within 10 meters of distance and within 20 meters of altitude. For these reasons, we shifted from determining the maximum range and altitude of the system in urban and wooded terrain, to solely observing the effects of urban and wooded terrain on the system's ability to detect and track entities. Therefore, additional scatter plots similar to Figures 8 and 16 were not generated for the urban and wooded terrain experiments.

a. Urban Terrain

The area within the testing grounds that was used to simulate urban terrain consisted of abandoned large containers, trucks, buses, and trailers. Although this area did provide ample material to simulate the opaque nature of a building or series of buildings, there were no opportunities to test the system's performance within a building or urban mock-up of any type.

The entities, if kept at a lower number, did not appear to affect the system's ability to detect entities in urban terrain. In the same way, movement by entities that the system was unable to detect did not enhance the system's ability to acquire the entity. Both human and vehicular entities did show a trend of the system's ability to maintain track of an entity after entering an area where it previously could not detect the entity if the entity was detected in open terrain prior to entering the contested area. For instance, human entities were not easily detected within bus doorways as demonstrated in Figure 20, nor were vehicle entities detected within the shadows of containers being used to simulate buildings. However, if a human entity was detected outside of the bus doorway, and then entered the doorway, the system was able to maintain an intermittent track of the human. In the same way, if a vehicle was detected within an open area in the sunlight, the system was able to

maintain track of the vehicle after it entered a shaded area as long as it did not lose its line of sight with the entity.

The inability of the system to recognize a human entity emerging from a bus emergency hatch as shown in Figure 22 proved hard to explain. While it may be assumed that the SPOTR software has been trained to detect full humans instead of half humans, this factor became further complicated when the system would occasionally detect the legs of a human in sunlight while the upper half of the same entity was concealed by a shadow. Perhaps the system more readily identifies the legs of humans rather than their more unique upper body features, which would explain why horses facing a sUAS were at one point misidentified as human entities during the discovery experiments.

In the same way, the system's failure to identify entities behind both tinted and clear glass windows was another conundrum that could not be fully explained. It presented another situation where a human could easily identify an entity with the naked eye, but for whatever reason the system could not. Once an entity was placed behind a glassless window, however, a situation that makes very little difference to the human eye visually, the system was able to detect humans intermittently. Similarly, if one human entity were to walk past an obstacle as thin as a telephone poll while being tracked by the system, the system would give that entity a different tracking number. This analysis suggests that the SPOTR software requires significant improvements to operate in urban environments, or the cognitive workload of a human utilizing the system in urban terrain will increase.

b. Wooded Terrain

The area used to simulate wooded terrain originally consisted of a single tree, and later included multiple trees with ample spacing between each tree. At a later point in time when the system is more capable of identifying entities within shadows and limited blockage from tree branches, retesting the system in a more heavily forested area would prove beneficial. However, due to the significant hindrances experienced while testing among generously spaced foliage, for the purposes of this iteration of SATLAS, the tree-line used was more than adequate.

Only human entities were observed during the wooded terrain experimentation due to time and terrain constraints. Additional experiments where the system is provided the opportunity to detect and track vehicles beneath a tree-line could prove beneficial considering the system's greater range, altitude, and efficiency with detecting vehicles in comparison to human entities as demonstrated in open terrain.

As stated in Chapter III, once the SPOTR software was updated, it was able to detect human entities wearing brightly colored clothing within a tree's shadows if they were detected prior to entering the shadow. However, the moment that a sizeable branch interfered with the line of sight between the system and the entity being observed, the entity was lost. This slight improvement due simply to a software update implies that further training of the system with additional images in shadowed areas obstructed by tree branches could enable the system to more readily identify entities in wooded terrain.

3. Autonomous Activity Effects

The autonomous operation tracking experiments were the last experiments conducted for this thesis, causing these experiments to be severely limited due to time constraints and the limits of the platform. The autonomous tracking experiments were restricted to autonomously following vehicles and identifying nearby vehicles during this activity. The time needed to reprogram the system to test it with humans would have required an additional training day that the team was not afforded.

The Nibbler prototype used for this experiment had been programmed for the specific purpose of serving as an aerial guide to a land robot in an all-autonomous platform exercise being conducted by the AV engineers prior to and following this round of experiments. For this reason, the system would position itself immediately above and slightly in front of an entity that it intended to track prior to that entity's movement as shown in Figure 35. Once the vehicular entity began to move, the impressive speeds at which the Nibbler was able to track the vehicle implies that a similar or more advanced system would have no issues tracking a human entity on foot if the entity was attempting to evade the system in open terrain. The programming positioning of the platform, however, very likely resulted in the system losing track of an entity shortly after reaching

speeds in excess of 15 mph. Further experimentation in which the platform was trained to track an entity from rear or flank of an entity with greater stand-off could prove of value.



Figure 35. Nibbler Positioning Prior to Autonomously Tracking an Entity

An impressive feature observed with the Nibbler system during its autonomous activities was its ability to identify not just other vehicles in vicinity of the vehicle that it was autonomously tracking, but also the direction that the vehicles were facing as shown in Figures 29 and 30. When the possibility of adding this additional feature of designating the direction that detected humans were facing was discussed, AV's engineers stated that it would be much more difficult. However, if this ability was possible, it could prove valuable during operations in denied terrain by SOF personnel.

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V. CONCLUSION

The objective of this research was to continue refining the foundation laid by previous iterations of SATLAS in pursuit of creating a SPOTR/sUAS system capable of enhancing the FP and SA of SOF elements in future operating environments. As a necessity, the majority of the the experiments continued to research and develop pillar two, integrating object recognition software into a sUAS platform. Pillar one was reengaged as man-packable sUAS platforms were purchased and tested on their ability to integrate with the software. Pillar three was briefly initiated through minor autonomous activity experiments both with and without the SPOTR object recognition software.

Although issues were encountered following the acquisition of our primary developer, Progeny Solutions, the wider customer base and resources of their now parent company, AV, assisted in rapidly advancing the SPOTR software's range from 20 meters to over 200 meters for human entities, and over 500 meters for vehicles in just nine months' time. Even though our level of involvement, and the intellectual property that NPS could own in the SATLAS project had drastically changed as a result of this merger, it benefited our research. The benefit of a federal-private partnership to advance defense goals and objectives was made clear once again.

A. SUMMARY

The SATLAS project has had numerous highs and lows. At its current state it maintains vulnerabilities and value, but nowhere near the value it could bring if given proper attention, funding, and support. The following two sections will go more in depth on those two topics.

1. Where We Are

As of the conclusion of this iteration of SATLAS, a suitable man-packable semi-autonomous sUAS platform has been identified as preferred to pair with the SPOTR software, and significant advances have been made with the object recognition software to facilitate smoother transitions to future field experimentation when possible. The sUAS

platform identified by both DIU and us as having significant potential to meet the needs of a SOF maneuver element while minimizing their cognitive workload is the Skydio X2D. The X2D's autonomous features and powerful camera make it one of the best sUAS options for complementing the features of the SPOTR software to enhance the SA and FP of a SOF maneuver element. The SPOTR software itself, previously reaching a max effective range of 20–30 meters less than a year ago, has expanded its capabilities to over 200 meters for detecting human entities, and over 500 meters for detecting vehicle entities. Despite these positive advancements, there are also vulnerabilities worth noting.

The X2D's significantly reduced capabilities during low light operations, its auditory signature, its minimal inclement weather resistance, and its battery life still leave much to be desired for a SOF element intending to use this resource in a variety of MDO environments. In the same way, the SPOTR software's consistency in more complex environments, such as urban and wooded terrain, are in need of further improvements. In its current state, if an entity being observed in an urban or wooded environment was aware of the SPOTR/sUAS system's presence, it would take very little effort to cause the system to lose track of, or the ability to detect the entity all together, significantly reducing its tactical utility.

2. Where We Want to Be

Most SOF elements conduct their key missions during hours of limited visibility. A platform that intends to augment SOF needs to perform with high reliability during these conditions. Some of the best attributes of the X2D, such as its obstacle avoidance, are severely reduced if not incapacitated during limited light environments as a result of the use of thermal cameras and other secondary assets. In the same way, while operating in sensitive environments, being able to maneuver through denied territory without broadcasting the presence of U.S. forces with an easily detectable auditory signature is preferred. Although the X2D is one of the most capable sUAS systems we've evaluated, it's also one of the loudest.

Concerning the X2D's capability to operate in a variety of environments, the X2D platform is currently optimized to conduct operations in mild, arid climates. However, as

international relations and discussions of global power continue to fluctuate, the variety of environments that a platform would need to be able to operate in continue to fluctuate as well. The final platform that is paired with the SPOTR software in a preferred end state will require the ability to operate in dry, wet, cold, and hot conditions with little effect on the platform. While operating in these environments, the platform needs to be able to maintain its aerial position for as long as possible to minimize the moments where a SOF element's situational awareness is reduced as batteries are being changed out. Although a 35-minute battery life is impressive, in accordance with the length of an average special warfare SOF mission, a platform would preferably be able to remain in flight for an hour if not longer.

The SPOTR software's ability to accurately and consistently detect and track multiple entities in a variety of environments is critical. Maintaining this performance at ranges exceeding the maximum effective range of the small arms weapons being utilized by enemy combatants while operating in open terrain is preferred to increase the FP posture of a SOF element. While operating in wooded or urban terrain, the software needs to be able to rapidly detect entities being concealed by trees or shadows. It also needs to be able to maintain the same tracking number for specific entities of interest that enter and exit buildings, or that hide and reemerge from behind obstacles while being observed by the system.

From an autonomous perspective, the SPOTR/sUAS must augment an operating SOF element while reducing the cognitive workload as much as possible. The ability to autonomously zoom in on entities or areas of interest; to autonomously detect optimal flight routes, altitudes, and ranges to observe from; and to autonomously alert a SOF element of entities of interest through auditory signals would significantly decrease the potential workload of a SOF user. In a similar way, to detect and recommend optimal routes and courses of action for maneuvering SOF elements based off of potential threats along an active route would enhance the FP of a team in ways that have not yet been seen by organic platforms.

B. FUTURE WORK

This section provides recommendations for future work in the SATLAS project to continue the previous efforts to develop a man-packable organic sUAS capable of operating semi-autonomously while using object recognition software. Any following research would benefit from continued efforts with the SPOTR software to ensure that it is capable of operating in a continuum of environments, and to ensure that its maximum effective range and altitude are optimal.

Reincorporating the M440 and the X2D into field tests with the SPOTR software, once their updates and necessary alterations are complete, would prove invaluable. Their more sophisticated features would very likely increase the SPOTR/sUAS performance considerably. Their autonomous features would also enhance the number of applications in which the platforms could support real-world SOF simple and complex missions. As the potential MDO scenarios become more complex, adding platforms to a SOF element to test the benefits of cooperative augmentation of a SOF element should be considered. Observing the feeds on the ATAK, or a similar graphical user interface, would assist in user familiarization with the system and its capabilities. Adding in other sUAS and aerial platforms as additional categories of entities to detect and react to could also prove invaluable in enhancing a SOF element's ability to avoid detection by unfriendly platforms.

Upon further experimentation, the SPOTR/sUAS system could be pushed to a limited number of SOF teams for further testing and evaluation. After individual training and familiarization sessions, the system could be tested during team-on-team training to confirm or deny their potential value in scenarios in a future MDO environment.

C. FINAL THOUGHTS

Future warfare will undoubtedly include both SOF elements and sUAS platforms for state and non-state actors alike. Using conventional forces for anything short of fully declared conflict has become domestically and globally intolerable. If whole-of-nation wars are conducted by democratic states, popular opinion will encourage the restriction of most kinetic and non-kinetic military operations to small scale missions by SOF elements. Even for the larger scale wars that are waged at a magnitude that few care to seriously

entertain, SOF will play a critical role that cannot be overlooked. In the same way, future nations engaging in small and large-scale wars who wish to maintain their competitive edge will pursue sUAS advancements to successfully compete against their adversaries who will unquestionably be doing the same.

At the rate of technological advancement, thoughts and ideas become reality in a matter of months if not weeks. The nation who will win the conflicts of the future will not be the nation that hesitates due to uncertainty and unfamiliarity with the way that wars may be waged, but rather the nation who aggressively pursues possibilities, allowing that nation to make the rules rather than being forced to abide by another's.

The SATLAS project is just one attempt to lay a foundation for an adjustment not for what war could be, but what it will be. We can and must rapidly leverage the technology available to provide SOF elements with a capable, versatile sUAS. If our emerging MDO doctrine is accurate, the insights from warfighters such as the participants in this SATLAS project may be our best approach to bringing the potential FP enabling enhancements to ISR and to the field. Various organizations hold the necessary pieces to expedite this project and other similar efforts in the direction of success. You do not have to be an authoritarian nation to put your best assets together towards a common goal, you just have to be willing to work together. Perhaps the small plaque that President Reagan kept on his desk puts it best: "There is no limit to what a man can do or where he can go if he does not mind who gets the credit." Where our country stands ten years from now will be a clear proclamation of whether we heeded this wisdom as a nation united, or whether we continued to imprudently charge forward as a nation divided.

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